Proceedings of Conference on Low Frequency Noise and Hearing", Aalborg, Denmark, May 7-9, 1980

Møller, Henrik; Rubak, Per

Publication date:
1980

Proceedings

Conference on
Low Frequency Noise and Hearing
7–9 May 1980 in Aalborg, Denmark

Edited by
Henrik Møller and Per Rubak

AALBORG UNIVERSITY PRESS

Proceedings of the Conference on

Low Frequency Noise and Hearing

7–9 May 1980 in Aalborg, Denmark

Proceedings

Conference on
Low Frequency Noise and Hearing
7–9 May 1980 in Aalborg, Denmark

Edited by
Henrik Møller and Per Rubak

AALBORG UNIVERSITY PRESS

Proceedings of the Conference on
Low Frequency Noise and Hearing,
7–9 May 1980 in Aalborg, Denmark

ISBN 87–7307–061–0

Distributed by:
Aalborg University Press
Box 159
DK–9100 Aalborg
Denmark
Telephone: (08) 15 50 31 (national)
+45 8 15 50 31 (international)

COMMITTEES

Organizing Committee:

Jørgen Bach Andersen, AUC, *(chairman)*
Henrik Møller, AUC, *(secretary)*
Paul Francois, France
Fritz Ingerslev, Denmark
Bjarne Kirk, AUC
R. Lawrence, England
Per Rubak, AUC

Program Committee:

Henrik Møller, AUC, *(chairman)*
Per Rubak, AUC, *(secretary)*
Per V. Brüel, Denmark
H. G. Leventhall, England
Ole Juhl Pedersen, Denmark

Social Committee:

Dorte Bach Andersen
Jette Damkjær
Bjarne Kirk
Grethe Møller

SPONSORS

Federation of Acoustical Societies of Europe
Institute of Acoustics, England
Danish Acoustical Society
IEEE Denmark Section
Commission of the European Communities
Aalborg University Centre

Proceedings of the Conference on Low Frequency Noise and Hearing
7–9 May 1980 in Aalborg, Denmark

Preface.

The first international colloquium concerned only with infrasound was held in Paris 1973. At this colloquium several effects of infrasound on human beings were presented and reviewed. An effort was also made to suggest some very preliminary criteria for infrasonic exposure. In the following years a number of new results were published, and several of them indicated that the limits for acceptable infrasonic exposure should be lowered considerably, if psychological effects were to be taken into account. Several countries have started more systematically to investigate infrasonic sources and to registrate complaints from people being disturbed by infrasound.

Infrasound is traditionally defined as sound waves with frequencies below 20 Hz. However, when considering the psychological and physiological effects of noise it does not seem to be profitable to divide the research into one part below 20 Hz and another above. Therefore this conference has been proposed to cover both infrasound and the lower part of the normal hearing range up to about 100 Hz.

The present international conference was initiated during the Meeting on Low Frequency Noise at Chelsea College, London, 1979. It was the general opinion that so much research is being done within the field of low frequency noise that an international conference is needed. Furthermore, a few countries have established Recommandations for measurement of infrasound and permissible level of infrasonic exposure. These preliminary standards diverge noticeably from each other, probably because the knowledge about the effects of low frequency noise is not sufficient at present.

It is a serious problem that more experiments are needed to establish loudness and annoyance ratings as functions of the intensity level and temporal course. At the moment a study group under ISO/TC 43 is working on standardization of measurement procedures for low frequency noise.

The program of the present conference contains 4 invited survey lectures and 26 contributed papers, which are grouped in 6 sessions each concerning a specific area. We hope the conference may clarify some of the problems, in this way establishing a better background for national and international standards. This would give the governments a tool for protecting the public against excessive low frequency exposure.

Henrik Møller and Per Rubak
Editors
on behalf of the Program Committee

F. ABATEMENT

Conference on
**Low Frequency Noise
and Hearing**

7–9 May 1980
at Aalborg University Centre
Aalborg, Denmark
Proceedings edited by
Henrik Møller and Per Rubak

THE OCCURRENCE, MEASUREMENT AND ANALYSIS OF LOW FREQUENCY NOISE

H. G. LEVENTHALL, CHELSEA COLLEGE, UNIVERSITY OF LONDON,
PULTON PLACE, LONDON, SW6 5PR.

Summary Problems encountered in the measurement and analysis of low frequency noise are discussed, including the performance of conventional instrumenation at the lower end or below the normal limits of its range. Examples are given of the occurrence of low frequency noise from a variety of sources.

Detection and Measurement of Low Frequency Noise

Instrumentation which is currently available makes the detection, recording and analysis of low frequency noise a relatively simple matter. However, this equipment may be very expensive and it is possible to continue to use some of the less sophisticated techniques which were employed before the development of modern equipment. It is notable that the stimulus towards the development of low frequency acoustic monitoring equipment came from the interest in sonic boom about 10 years ago, not through a general interest in low frequency noise.

Detection of Low Frequency Noise

Early designs of special microphone dealt with the infrasonic range and were, in general, of limited use in the lower audio frequency range.

The microphones included:

a) Condenser Microphone (1) The microphone diaphragm was enclosed in a cavity, external pressure fluctuations being passed through a needle valve which gave a controlled leakage rate into the cavity. A second needle valve to the rear of the diaphragm controlled the pressure equalisation rate, thus selecting a band of frequencies. Frequencies less than about 1 Hz were passed without attenuation whilst the pressure equalisation leakage was much slower, to permit the detection of frequencies below 1 Hz, but to give equalisation for atmospheric pressure changes.

b) Moving Coil Microphone (2) An acoustic resonator was incorporated into the microphone in order to raise the low frequency response. The response of the microphone was typically from about 6 Hz to 100 Hz.

c) Optical Detector (3) A large cylinder (volume 120 litres) was closed at one end with a rubber diaphragm to which a small mirror was attached at the centre. Movement of the diaphragm was detected by light reflected from the mirror through a screen in which the opacity was dependent on its length, before falling on to a photocell. The useful range was from about 0.1 Hz to 40 Hz.

d) Solion Infrasonic Microphone (4) An electrolytic solution was contained by flexible diaphragms and differential pressure fluctuations cause flow of the electrolyte. This was converted to a fluctuating electrical output. The frequency range was from 0.0001 Hz to 30 Hz.

e) Thermistor Microphone (5) Air flow over a thermistor bead carrying a steady current causes cooling of the bead and a change in resistance, which may be detected by connecting the thermistor in a bridge circuit. Rectification was avoided by using a second thermistor adjacent to the first so that it was warmed by the heat lost from the first one, thus ensuring that the bridge output changed polarity as the air flow direction changed. The frequency range was from about 0.001 Hz to 22 Hz.

The microphones described above are not suitable for the full range from about 10 Hz to 150 Hz which might be involved in a study of low frequency noise in towns and industry. However, more conventional microphones are also available.

Piezo-electric Microphone The low frequency limit of a microphone employing a diaphragm depends on the pressure equalisation hole connecting the rear of the diaphragm to the atmosphere. If this hole is blocked or omitted, and the capsule sealed, the diaphragm will, ideally, respond to static pressure changes. The diaphragm deflection is transmitted to the sensing element which may not be able to maintain its response down to very low frequencies because of charge leakage through external resistance or, in the limiting case, through the leakage resistance of the element itself, during the fluctuation of the incident pressure. A piezo-electric microphone has been adapted to operate down to 0.1 Hz (6). A B and K 4117 microphone, which normally has a lower limit of 3 Hz, was modified by blocking the equalisation hole and using a high input impedance amplifier in the first stage of signal amplification. Residual air leakage limited the acoustic low frequency cut-off to 0.1 Hz. The electrical low frequency cut-off, f, was obtained from the microphone capacitance (4000 pF) and amplifier input resistance ($10^9\ \Omega$) using $2\pi fRC = 1$. Hence $f = \frac{1}{2\pi RC} = 0.04$ Hz giving the frequency at which the electrical response of the system is 3 dB down. The Pons type MIF70 is a piezo-electric microphone specially designed for infrasound. It has a diameter of 330 mm and an upper frequency limit of 20 Hz.

Condenser Microphones The condenser microphone may be used in a similar manner to the piezo-electric microphone described above. However, since the capacitance of a condenser microphone is much lower than that of the piezo-electric (say, 60 pF compared with 4000 pF), the lower frequency limit might be determined electrically rather than acoustically. For example, a microphone of capacitance 60 pF used with an amplifier having input resistance of $10^9\ \Omega$ has a lower limit of about 2.5 Hz due to the time constant of the electrical system, even though the microphone acoustic cut-off frequency may be lower. A condenser microphone also lends itself to use in a high frequency tuned circuit, or balanced bridge system, operating in the megahertz region. Diaphragm movement in the tuned circuit causes a frequency modulation which is subsequently demodulated to regain the low frequency. Diaphragm movement in the balanced bridge causes an amplitude variation of the high frequency which is detected to give the original waveform. Commercial frequency modulation systems are available, e.g. the B and K Type 2631 carrier system with either one inch or half inch microphones, and the Sennheiser MKH-110-1. These microphones respond over the audio as well as the infrasonic region.

Microphone Calibration

It is desirable to calibrate a microphone in the range in which it is to be used. Conventional 1000 Hz piezo-electric calibrators or 250 Hz pistonphones lie outside this range. The pistonphone may be run at low speed by reducing the motor voltage. However, although the peak displacement remains unchanged, errors may occur at lower frequencies when heat loss to the walls of the pistonphone causes a reduction of pressure during the period of the diaphragm displacement. The error begins to become apparent when the pressure changes are turning from adiabatic to isothermal and has maximum value of about 3 dB. The effect, which is minimized by using a large volume compared with the surface area of the pistonphone cavity, depends on the ratio of volume to surface area of the cavity and inversely on the square root of frequency.

An alternative method of calibration employs a piston driven by a constant force, instead of with constant displacement. The driving force is obtained from an electro-magnetic vibrator fed with constant current. The air cavity is small in order to ensure that the overall stiffness of the system is due to the enclosed air and not the vibrator suspension. Then, if the pressure drops due to heat conduction at low frequencies, the constant force maintains the required level.

Recording of Low Frequency Noise

It is not always possible to carry analysing equipment to the site of a low frequency noise and tape recording is necessary. A wide range of multi-channel frequency modulation recorders is available, giving a response down to zero frequency. However, these are very expensive. It is possible to modify a conventional direct tape recorder to cover the low frequency range by using an external frequency modulation unit. The design of such units is fairly simple since the basic elements required are available as integrated circuits. We have found that a voltage to frequency converter set at about 6 KHz gives a good response up to about 450 Hz when the voltage controlled frequency modulation is replayed through a frequency to voltage converter. The system is illustrated in Fig. 1 which also shows a typical frequency response. A high impedance input amplifier following the microphone ensures a good low frequency response whilst the low pass filter removes higher frequencies which may cause overloading. The frequency modulated output consists of rectangular pulses which are recorded on the tape. Demodulation restores the low frequency fluctuations. If the unit is used with a two-channel (stereo) tape recorder, there is an overlap with the normal audio channel, permitting recording from low infrasonic frequencies throughout the audio frequency range.

Analysis of Low Frequency Noise

Recent years have seen considerable development in analyser techniques. There are a variety of low frequency analysers, giving either contigious band or narrow band analysis, mostly operating on Fast Fourier Transform techniques. These analysers are extremely useful instruments, easy to use, giving a clear presentation of results, but are very expensive. For example, if one was to combine a low frequency sound level meter and commercial FM tape recorder for field measurements, with an FFT analyser for laboratory analysis, the cost is likely to be in the region of £12,000 to £15,000 depending on choice of instruments.

Analogue analysers for low frequencies using active filters based on operational amplifiers, can be constructed fairly easily and assembled to produce a bank of octave - 1/3 octave band filters. However, a 1/3 octave filter centred on 10 Hz has a bandwidth of about 2.3 Hz and slow fluctuations in output level will result from the analysis of wideband noise, requiring a long averaging time to ensure accuracy. The relative error is given by $e = 1/\sqrt{BT}$ where B is the band width and T is the averaging time. This shows that if the relative error is to be 5%, an averaging time of about three minutes is required. It is apparent that narrow band analogue analysis at low frequencies can be a very lengthy process and digital methods are to be preferred when possible.

Typical Sources of Low Frequency Noise

There is no basic difference between sources of low frequency noise and sources at higher frequencies. Low frequency noise may be produced by pulsating and reciprocating machinery, resonance, turbulence and impulses.

Low Frequency Noise in Industry

Low frequency noise in industry is produced by compressors, combustion processes, large vibrating surfaces, etc. A typical compressor noise is shown in Fig. 2, which is also representative of noise from slow speed engines. There are major peaks of about 110 dB in the 25 and 50 Hz bands. An example of combustion noise is shown in Fig. 3. Here there is a peak of about 85 dB at 32 Hz. This is probably due to a resonance in the boiler system. Combustion noise in a factory is shown in Fig. 4. High levels of noise have also been measured from a Tuyere Furnace which produced 123 dB at 25 Hz at the charging platform and caused noise annoyance in nearby domestic buildings. A level of 120 dB at 25 Hz has also been produced by a shaker table in a foundry knockout plant.

Low Frequency Noise in Transport

Here one is concerned with either the effect of the low frequency noise on the occupants of the transport or with the environmental effect. There have been several series of measurements of low frequency noise in cars and lorries (6) (7) (8). In general, for saloon cars, when all windows are closed there is increase of level as the frequency drops, largely contributed by turbulence and varying as $P \propto V^a$. P is the acoustic power in the low frequency range, V is the vehicle speed and the exponent $a \simeq 3$. When the vehicle is travelling at speed with a rear window open, there is a low frequency peak, caused by resonance within the vehicle body itself. A typical effect is shown in Fig. 5. The high peak may cause distraction and discomfort for the driver. Low frequency noise in commercial vehicles is often of broader peak and accompanied by considerable vibration. Buses are also a source of low frequency noise

(9). Fig. 6 shows the noise produced as a bus pulls away from standing. There is a high peak at the firing frequency, within 63 Hz band, which is typical of heavy vehicles. Noise from a bus external to and internal to a house is shown in Fig. 7. The bus was travelling at approximately 50 km an hour and produced a peak in the 10 to 20 Hz region. The external noise is modified by the building structure to give a more unbalanced spectrum which migh result in vibrations of lightweight elements of the building.

Low frequency noise in trains is a problem more for the driver than for the passengers and concern has been expressed on the effects of diesel engine noise on the fatigue and vigilance of train drivers. Levels in excess of 100 dB have been measured up to about 100 Hz depending on wind conditions and speed (10).

Ships' engines are a strong source of low frequency noise. The noise in the engine room of a cross-channel ferry and the noise in a cabin is shown in Fig. 8. These spectra are typical of noise in diesel engine ships. There are high levels produced at the engine frequencies resulting in uncomfortable acoustic conditions in the areas of accommodation as well as on the bridge. In the ferry shown in Fig. 8, the levels on the bridge were very similar to those in the cabin, there being a pronounced peak at 20 Hz.

Low frequency noise in air transport is usually masked by the higher frequencies, except for helicopters which have peaks at the blade rotation frequencies. Fig. 9 shows the noise inside two small helicopters. Low frequency noise from jet engined aircraft falls off rapidly below the peak in the turbulence spectrum. Larger engines are resulting in lower peak frequencies. For example, the take-off noise of a B707 has a broad peak at about 160 Hz whilst a Tri-Star has the peak centred at about 100 Hz. It is unlikely that engines will increase in size sufficiently to reduce the peak to infrasonic frequencies, although this does occur with large rocket engines.

Environmental Low Frequency Noise

Environmental low frequency noise results from a number of sources, some of which may be difficult to trace. Any of the sources described above produce noise in the external environment. A stream of traffic results in high levels of low frequency noise. Fig. 10 shows the levels outside and inside a double-glazed house alongside a busy road. The peak at 63 Hz is expected from a predominance of heavy vehicles, although the peak may change to the 125 Hz band for fast flowing traffic.

Ventilation noise may also be a problem in the low frequency region. Fig. 11 gives the noise produced by the extract system of a poultry house at nearby residences. There were two fans running at slightly different frequencies giving a double peak in the spectrum at about 60 Hz and harmonics. The resulting beat between the two frequencies was a particularly annoying characteristic of the noise. Fig. 12 shows ventilation system noise in a hospital ward. There is a complicated spectrum produced by generator room noise and ventilation noise but the peak of 75 dB at about 60 Hz was traced to the ventilation system. There was a level of 90 dB in the adjacent toilet which was being ventilated.

There is also low frequency noise in isolated parts of the country-side. This may be due to distant industrial, traffic or other sources, or to wind and other meteorological conditions. The noise normally fluctuates in level. Fig. 13 is a statistical analysis of noise in a very quiet country location. There were birds and farm animals in the vicinity, but if the L_{90} level is taken as background, it is seen that there is a peak in the region of 10 Hz, although this is well below the threshold of audibility. In other circumstances, particularly nearer to industrial areas, the low frequency levels may be higher and the average levels reach the region of the normal threshold (11).

Conclusion

It has been shown that there are a large number of low frequency noise sources. Many sources which have conventionally been considered only in the audio frequency range produce high levels at low frequencies. Additionally, there are other sources whose energy lies predominantly in the low frequency region. The dBA measurement which is often taken, obscures the full extent of low frequency noise. It is not uncommon to find that the dBC or linear reading of a sound level meter is 20 dB greater than the dBA reading, thus indicating a high low frequency content. A comparison of dBA and dBC is a quick way of assessing the low frequency element of a noise, and the ear should also be included, since careful listening is often the simplest way to detect significant low frequency noise.

References

1. Baird, F. and Barwell, C. J., (1940). Recording of Air Pressure Oscillation Associated With Microseisms at Christchurch, New Zealand, J. Sc. Tech. 21B, 314-329.
2. Vakhitov, Ya. Sh. (1964). A Highly Sensitive Infrasonic Moving Coil Microphone, Soviet Physics (Acoustics) 10, 199-200.
3. Gavreau, V., Condat, R. and Saul, H. (1966). Infra-sons, Generateurs, Dectecteurs, Proprietes Physiques, Effects Biologiques, Acustica 17, 1-10.
4. Collins, J. L., Richie, W. C. and English, G. E. (1964). Solion Infrasonic Microphone, J. Acoust. Soc. Am. 36, 1283-1287.
5. Fehr, U. (1970). Infrasonic Thermistor Microphone, J. Aud. Eng. Soc. 18, 128-132.
6. Hood, R. A. and Leventhall, H. G. (1971). Field Measurement of Infrasonic Noise, Acustica 25, 10-13.
7. Tempest, W. and Bryan, M.E. (1972). Low Frequency Sound Measurement in Vehicles, Applied Acoustics 5, 133-139.
8. Williams, D. and Tempest, W. (1975). Noise in Heavy Goods Vehicles, J. Sound Vib. 43, 97-107.
9. Hassall, J. R. (1976). A Review of Low Frequency and Infrasonic Noise Affecting London, M.Sc. dissertation, Chelsea College.
10. Willingale, B. J. (1979). Personal Communication from Australian Federated Union of Locomotive Enginemen.
11. Leventhall, H. G. (1980). Annoyance Caused by Low Frequency/Low Level Noise. Proceedings Conference on Low Frequency Noise and Hearing, Aalborg.

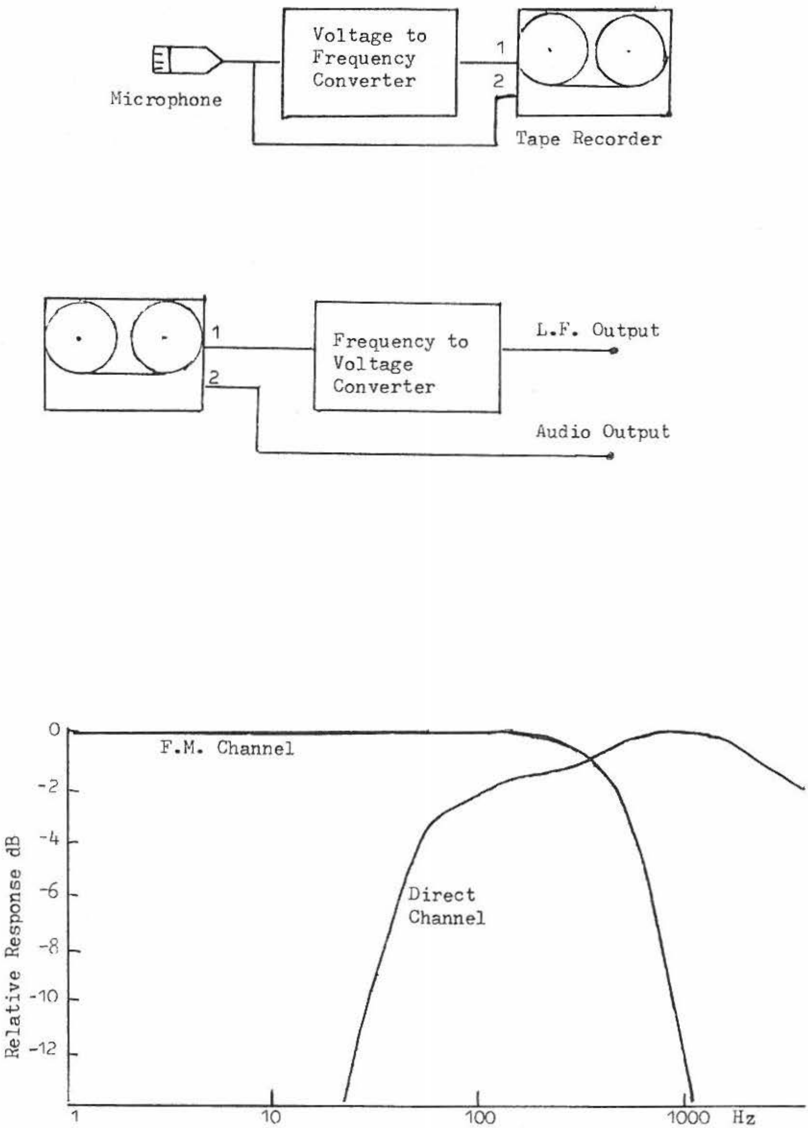


Fig. 1 Low Frequency Recording and System Response

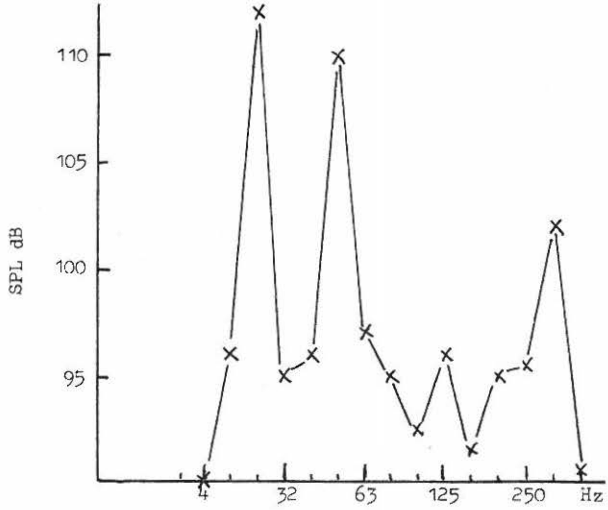


Fig. 2 Compressor Noise

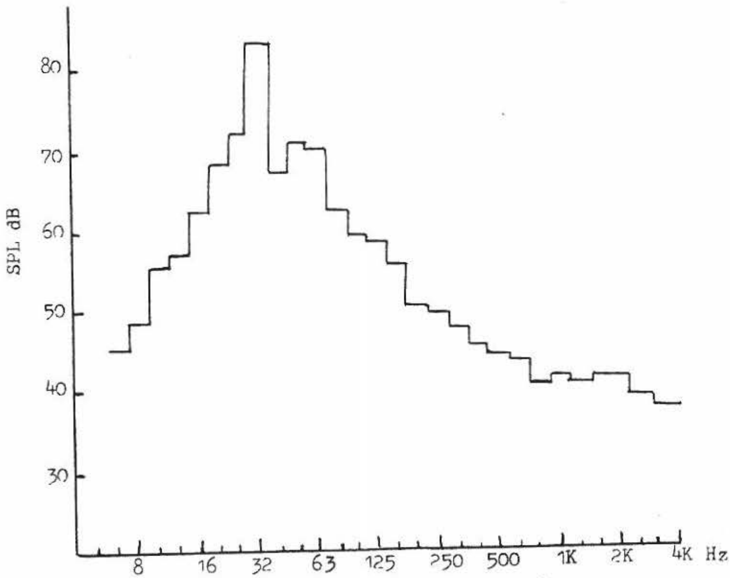


Fig. 3 1/3 Octave Analysis of Boiler Noise at 75 m

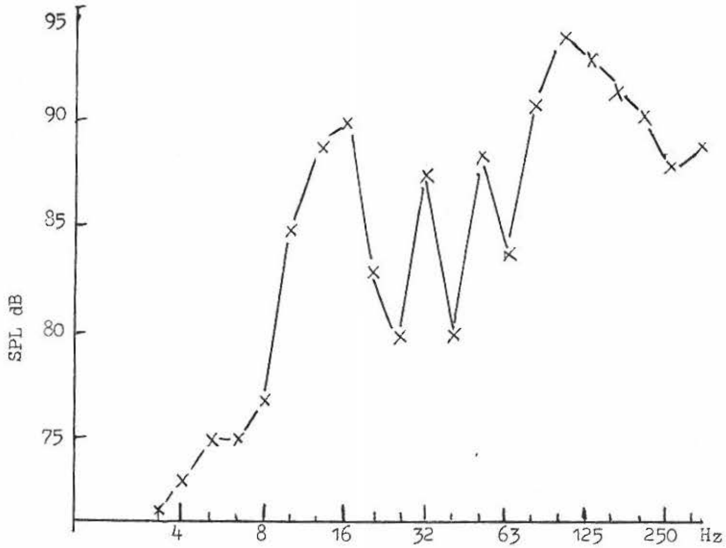


Fig. 4 Combustion Noise

Fig. 5 Noise in Saloon Car

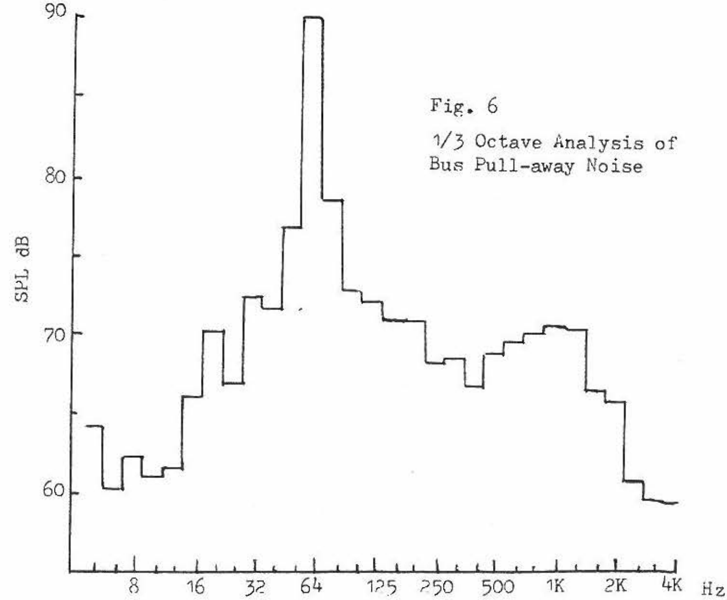


Fig. 6

1/3 Octave Analysis of Bus Pull-away Noise

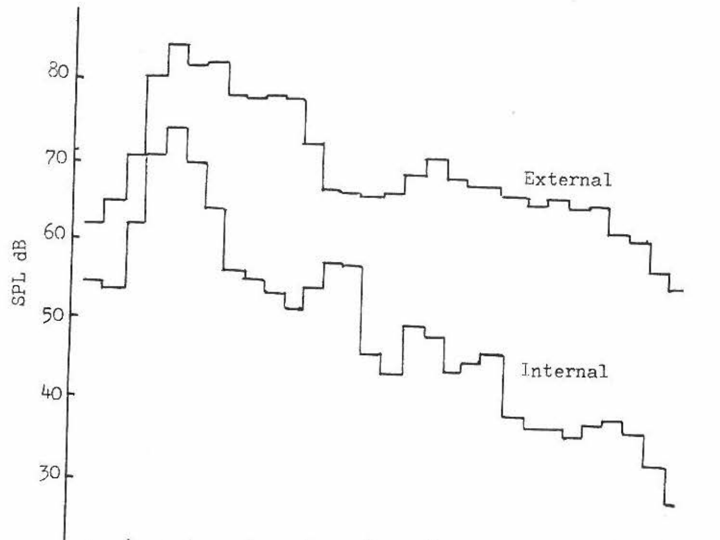


Fig. 7 1/3 Octave Analysis of Bus Drive-by Noise

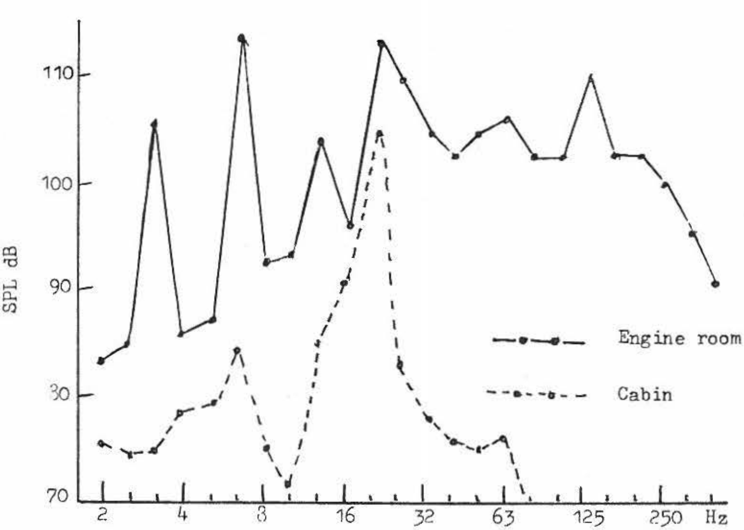


Fig. 8 Noise in Ship (1/3 Octave Analysis)

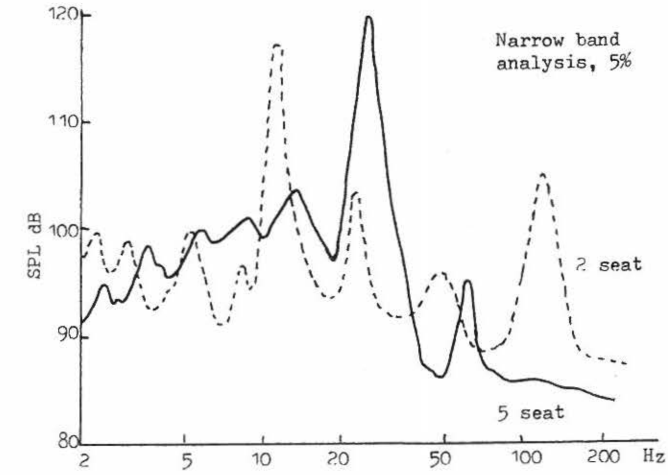


Fig. 9 Helicopter Noise

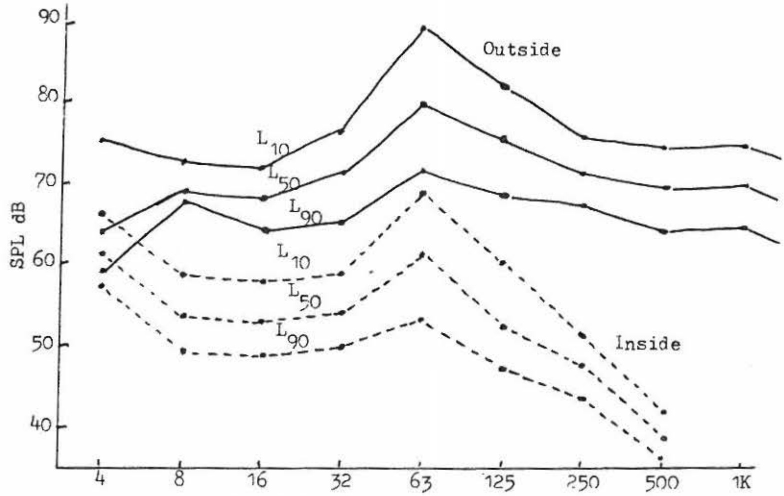


Fig. 10 Octave Band Centre Frequency Hz
Noise Outside and Inside a House

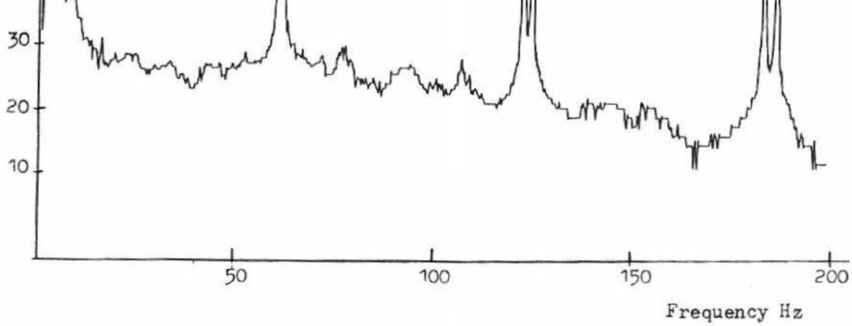


Fig. 11 Fan Noise From Poultry House

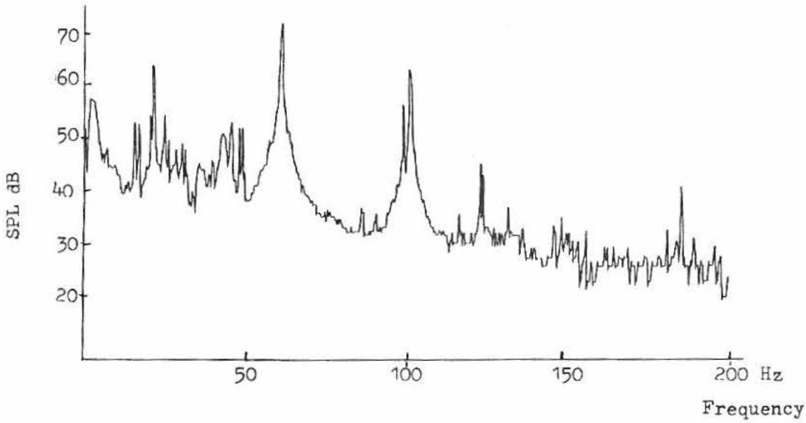


Fig. 12 Noise in Hospital Ward

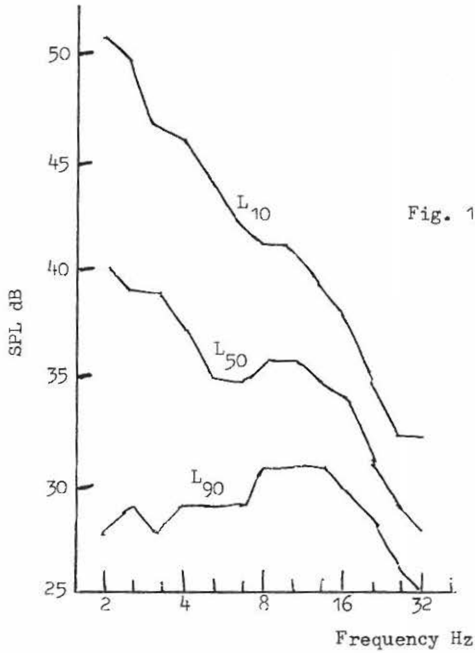


Fig. 13 Low Frequency Environmental Noise in Remote Area

Conference on
Low Frequency Noise and Hearing

7–9 May 1980
at Aalborg University Centre
Aalborg, Denmark
Proceedings edited by
Henrik Møller and Per Rubak

ASPECTS OF PSYCHOACOUSTIC PROCEDURES

Torben Poulsen
The Acoustic Laboratory
Building 352, Technical University
DK-2800, Lyngby
Denmark

SUMMARY

A short introduction to psychophysics is given. Various psychoacoustic procedures are described and discussed. Some of the considerations which must be taken into account during planning and performing of psychoacoustic measurements are given.

1. INTRODUCTION

Prior to evaluating data concerning human response to sound, it is nessesary to understand the methods used to obtain these data. If the methods are inappropriate or if they are used incorrectly, then the data might reflect only what an observer happened to respond to the sound-stimulus. Also it is worth to be aware of the uncontrolled factors associated with psychoacoustic testing.

1.1 Psychophysics

In psychophysics the observer is looked upon as a black box. See fig. 1. The observer is presented for the stimulus -

sound e.g., and the observer's response to the stimulus is the result of the measurement.

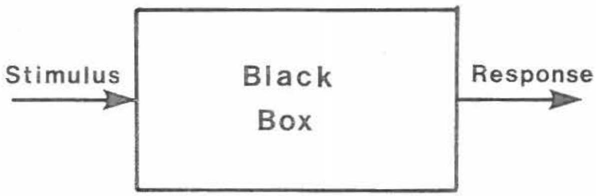


fig. 1
Schematic illustration of a psychophysical measurement

By repeating this measurement with various values of the physical stimulus it is possible to find relationsships between stimulus and response. The psychophysical measurement methods dealt with in this paper imply an active response from the observer e.g. pressing a button, saying "yes" or "no", writing on a piece of paper etc. Passive methods such as recording of nervepotentials from the brain, measuring heart rate or skin resistance etc. lies outside the limits of this paper.

References [1] and [2] are useful books within the field of psychophysics.

1.2 The Psychometric Function

Assume that we want to determine the threshold of a sound - a pure tone for instance. This might be done by presenting the tone at various levels to the observer. The observer is instructed to respond "yes" when he can hear the tone and "no" when the tone is inaudible. If this is done many times with the levels ranging from well above threshold to well below threshold a psychometric function as shown in fig. 2 may be constructed.

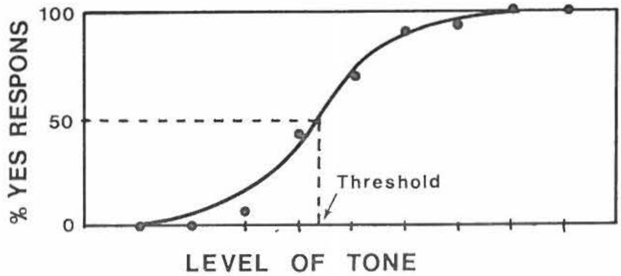


fig. 2

A typical psychometric function

Often the psychometric function is represented by a cumulative normal distribution. The function may be interpreted as the probability of getting "yes" response as function of the level of the tone. The threshold may then be defined as the level at which a positive response is equally likely as a negative reponse, the 50% point.

It must be noted that other definitions of the threshold are possible, e.g. the level corresponding to 75% "yes" responses may be chosed by an investigator as his definition of the threshold.

Although the psychometric function has been explained by a threshold measurement, this function is also used in connection with other psychophysical measures. In a loundness balance test, e.g. the function will represent the probability of getting a "louder" response as function of the level of the variable stimulus. The level corresponding to the 50% point is then labelled: point of subjective equality, PSE.

1.3 Observer Sensitivity and Bias

Assume that two observers took part in the above mentioned threshold measurement and that their thresholds (defined as the 50% point) deviated with 5 dB from one another. Is it then possible to conclude that the sensitivity of one of the observers is 5 dB better than that of the other? Unfortunately this is not the case. Only if the observers interprets the instruction in exactly the same way their sensitivity will deviate by 5 dB.

If the observers' criterions are different the result will be a combination of sensitivity and bias. One may respond on every soft sound that is barely audible, whereas the other responds only when he is quite sure that he can hear the tone. This is differences in criterion and thus in bias. Although the criterion is highly influenced by the instruction given to the observer, it is usually not possible to control the observers' criterions.

2. DISCRIMINATION PROCEDURES

These procedures are used to determine absolute thresholds or differential thresholds (just noticable differences, JND) and to perform balance tests.

2.1 Classical Methods

The classical methods are explained in the following by means of a threshold determination example, but they may of course be used also for other purposes.

Method of limits comprises descending and ascending series. The level of the stimulus is successively decreased (descending series) until the limit is reached where the observer is unable to hear the stimulus. In ascending series the level is successively increased to the limit where the observer reports that he again can hear the stimulus. By repeating this procedure a number of limits is obtained. The threshold may be computed as the average of all the limits. The Bekesy audiometer is a variant of the method of limits.

Method of adjustment implies that the observer is equipped with a device which can control the variable stimulus. The observer may then be instructed to vary the stimulus until it is just barely audible (= threshold). This method is often used with a bracketing technique where the observer turns the level up and down around the threshold making the variations smaller and smaller and thus encircle the threshold.

Generally the method suffer from the overadjustment effect, [2], [3], and also the physical properties of the regulating device may give some bias in the result [2], [4]. The main advantage of this method is that it is fast and simple.

Methods of constant stimuli. The experimenter chooses a range of levels within which he suppose the observer's threshold to be. The levels are equally distributed within the range and all levels are presented a certain number of times. Fig. 3 shows an example of a constant stimuli experiment.

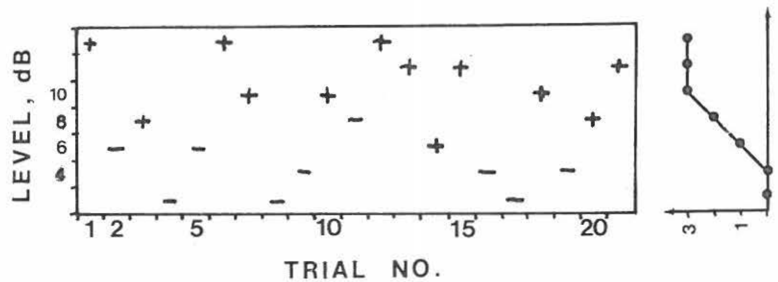


fig. 3

Example of the method of constant stimuli

The levels are presented in random order. At the end of the measurement the number of positive responses is counted for each level. From these counts the psychometric function may be found as shown in fig. 3.

In the example 3 replications per level is used, but this may be increased yielding a better determination of the psychometric function. On the other hand this will increase the measuring time with the risk of tiring the observer. The same considerations must be taken into account if the number of levels is increased.

It is important that the range of levels is wide enough to cover both extremes of the psychometric function. As the range is a compromise among number of levels, step size (resolution) and measuring time, this range will seldom cover both extremes for all observers. Thus for each observer the range must be shifted up or down according to the result of a few pilot measurements in the beginning - the experimenter must guess where the final threshold will be and place the range symmetrically around this expected threshold. In this way the experimenter may influence the result. If the range has been misplaced a little, a so-called adaption level bias may occur.

This bias is seen as a tendency of the observer to draw his 50% point to the midpoint of the range.

All these classical methods suffer from the general criterion problem.

2.2 Adaptive Methods

In adaptive psychophysical methods the value of the variable stimulus is changed from trial to trial depending on the previous responses from the observer. One of the main advantages of these methods is the ability to concentrate presentations within the range of most interest. The method of limits and the Bekesy variant are essentially adaptive methods.

In the adaptive methods the level is changed in accordance with rules which can be more or less complex. As some of these rules are difficult - or impossible - to manage by hand, the existence of computers has made it possible to implement and test several of the adaptive methods.

Up-down methods are excellent explained in ref. [5] and [6]. The simple up-down procedure may be explained by an example: determination of the threshold of a sound. If the sound is audible (positive response), the level of the sound will be decreased by a fixed value, the step size. The level is decreased one step as long as positive reponses are received. When a negative response is received the level for the next trial is increased one step. This is continued until a positive reponse is obtained and so on. Fig. 4 shows an example of data from a simple up-down procedure.

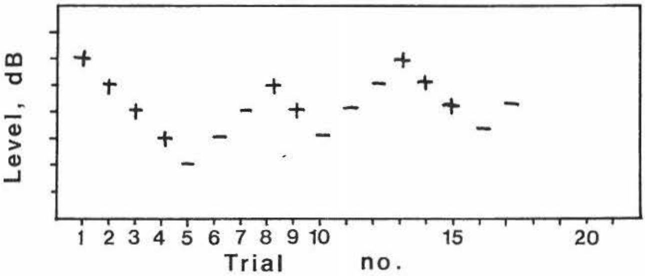


fig. 4

Typical result of a simple up-down procedure

The result of the measurement - the threshold - is determined by the mean of the reversals. Theoretically this will be the level which yields 50% positive responses.

If the step size is too big, an imprecise determination of the threshold will result as successive presentations are likely to shift from above threshold to below threshold.

If the step size is choosed very small, many trials are needed in order to get some reversals. This may tire the observer and an unwanted influence on the result may occur.

If other points than the 50% point are looked for the <u>transformed</u> up-down methods can be used. In the transformed methods the rules for increasing and decreasing levels depend on specific sequences of responses. The rule could for example be: increase the level after a negative reponse (-) and after a positive followed by a negative (+-); decrease the level after 2 positive responses (++). This rule will lead to the 70.7% level instead of the 50% level.

Another rule is: increase the level after any groups of 4 responses with 1 or more negative responses; decrease the level after 4 positive responses. This rule is typical for the BUDTIF-procedure, ref. [7] and will lead to a 84.1%

level.

<u>Method of maximum likelihood.</u> Another adaptive method is the method of maximum likelihood, MML, ref. [8] .

In this method the most likely psychometric function is estimated after each new response from the observer.

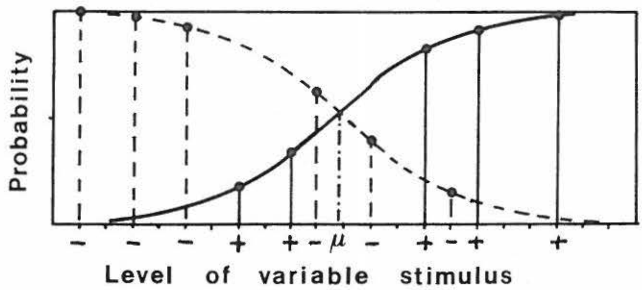


fig. 5

Psychometric function in the MML-procedure

Imagine that the positive (+) and negative responses (-) shown in fig. 5 have been obtained. The likelihood of the psychometric function shown in the figure is then found by computing the product of all the readings from the solid curve (positive responses) and all the readings from the dashed curve (negative responses). By means of an iterative procedure the psychometric function is then shifted along the abscissa and also the standard deviation (σ) is varied until the most likely combination of μ and σ is found.

As the result of the estimation must be finished shortly after the observer's response a computer is needed to perform the calculations.

The next presentation level is randomly placed 1 standard deviation up- or down from the μ value. This randomisation seperates the MML from other adaptive methods as the next presentation in these methods depends systematically on the previous responses.

In a simple model shown in fig. 5 only two response categories (+ and -) are allowed. If an equal response (=) is allowed - e.g. in a loudness balance test - a more elaborate model, which takes this response category into account, is needed.

2.3 Theory of Signal Detection

A modern discrimination procedure, theory of signal detection (TSD) has been widely used in resent years. The TSD procedure is similar to the method of Constant Stimuli, but in the TSD method it is possible to separate the observer's sensitivity from the observer's response bias. This very important facility is not present in the classical methods. Introductions to the TSD procedure may be found in ref. [1] and [9].

Assume that an observer is given 100 trials. In half of the trials a tone near threshold is presented and in the other half nothing is presented. The observer responds after each trial by saying "Yes, I heard a tone" or "No, I heard nothing". Now four situations are possible usually known as hit, miss, false alarm and correct rejection, see fig. 6.

Signal	Yes	No	Trials
Present	Hit 30	Miss 20	50
Absent	False alarm 10	Correct rejection 40	50
Respons.	40	60	100

fig. 6

Stimulus-response table

An example is shown where the observer responded YES 40 times and NO 60 times

If the experiment is repeated with the tone increased in level, it must be expected that the percentage of "hit" will increase as it is easier for the observer to hear the tone. Likewise the proportion of false alarm will decrease.

On the other hand the level of the tone may be kept constant and the bias of the observer changed. In the first run the observer may be told to say YES only when he is absolutely sure that he heard the tone. In the next run he may be told to respond YES, even if he is not quite sure that he heard the tone. This change in the instruction will not make the tone more audible, but the percentage of hits will increase. Also the percentage of false alarms will increase from the first run to the next.

The proportion of hits and false alarms may be used to obtain points on a so-called receiver operating characteristic, or ROC curve. An example of such curves is shown in fig. 7.

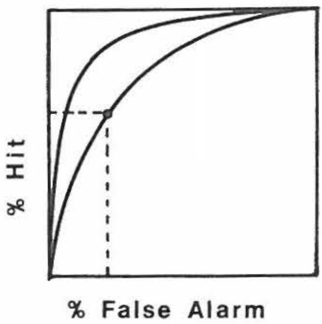


fig. 7

Example of two ROC curves
The point shown is taken from
the example in fig. 6.

By changing the observers' bias, different points on a single ROC curve is obtained. By changing the observers' sensitivity (e.g. by a change in signal level) points on different ROC curvers are obtained. Thus the ROC curves make it possible to separate bias effects from sensitivity effects.

The sensitivity measure is often given as d'. It may be understood as the difference between the means of the two evidence distributions respectively arising from the signal + background noise and from the background noise alone. The difference is measured in units of the distributions standard deviation.

3. SCALING PROCEDURES

Scaling is concerned with the relations between subjective responses to stimuli having some specified physical relation. Many scaling procedures are available, ref. [2] and [10], but only a few will be mentioned here.

Pair comparison. In this method the observer is presented for the stimuli in pairs and is asked to compare the two stimuli. Each stimulus in the experiment must be compared to each of the other stimuli. This may lead to a very time consuming experiment.

Ranking method. The observer may be asked to rank a (limited) number of stimuli. When many observers are used it is possible to obtain an average ranking of the stimuli.

Magnitude estimation. In this method the observer is asked to assign numbers to a particular attribute (loudness e.g.) of a stimulus. Often the observer is "helped" by a standard stimulus which may be given the value 100. If the stimulus is twice as loud as the reference it is given the value 200.

Interval and ratio judgement. In an interval judgement the observer may be presented 3 sounds, A, B, and C, where the level of B lies between the level of A and C. The observer is asked to adjust level B until the subjective interval from A to B equals the interval from B to C. In the ratio judgement the observer may be asked to adjust the level of a sound until it is e.g. twice as loud as another sound.

Rating scale methods. In such methods the observer rates the stimulus according to a scale given to him beforehand. Many scale principles exist, ref. [2], but only two will be mentioned here.

The graphic scale consists of a straight line, at which the observer marks his rating of the stimulus. See fig. 8.

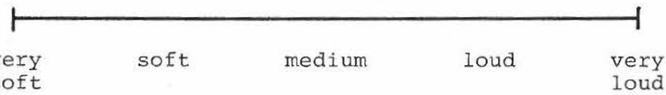


fig. 8

Example of a graphic rating scale

Many variations of this procedure exist. The line may be vertical, the line may be divided into segments, only the two extremes at the ends of the line may be given, etc. The result of the measurement is found by measuring the distance from the one end of the line to the observer's mark.

The numerical scale consists of numbers assigned to descriptions. Taking the descriptions from fig. 8 "very soft" may be given the number "1" and "very loud" may be given the number "5". The observer's response will then be one of the numbers from 1 to 5. Actually the numbers may be omitted and the descriptions used directly by the observer, but at the end the experimenter will use the numbers for calculations.

Reference [2] is recommended for a detailed discussion of these methods.

Task performance methods are used to study the influence from a given stimulus on observer's ability to perform different tasks. The task could be: problem solving, reaction time task, speech intelligibility, tracking a moving point by a pointer etc. For a discussion of the theories lying behind these methods the reader is referred to the litterature [11].

4. OTHER CONSIDERATIONS

During planning of experiments within the field of psychoacoustics, many considerations must be done. Some of them are mentioned in the following.

4.1 Stimulus Duration

The duration of the stimulus must be long enough to yield a stationary perception. Otherwise the temporal integration in the hearing mechanism must be taken into account. This will lead to a duration of about 1 sec. If more than one stimulus is presented, e.g. in a loudness balance test, the interval between them must be kept at at least 500 ms. This will reduce the influence from pre- and postmasking to a minimum. To avoid difficulties for the observer in comparing the two stimuli this pause should not exeed 1 - 2 sec.

Measurements of the temporal loudness summation in the hearing mechanism have shown that as a very first approximation the ear may be assigned a time constant of about 100 ms at levels well above threshold, whereas the time constant increases to about 200 ms at threshold, ref. [12]. It is questionable to what extent the temporal integration is frequency-dependent. Especially for the low frequency region information about this topic is needed.

In order to avoid to tire the observer, relaxing periods must be included. By using two observers at a time, it is possible to let one be observer 10 - 15 min. while the other relax and vice versa.

In measurements of annoyance it has been shown that the observer's responses are very unstable unless the stimulus last for a long periode of time, 20 - 30 min. A model for loudness and annoyance perception suggests that stimuli are evaluated in loudness to begin with, whereafter an annoyance evaluation will take over, ref. [13].

4.2 Shapening

It is obvious that the distortion of the stimulus must be kept at a minimum. Especially at low frequencies distortion products may interfere with the measurements due to the steep slope of the hearing-threshold. It must also be kept in mind that the time function and the frequency spectrum of a stimulus are linked together. A short tone pulse for instance, will have a spectrum that is clearly audible different from that of long lasting tone with the same frequency. Thus filters or shapers with controlable rise- and fall times may be used.

4.3 Experimental Design

A major part in the planning of an experiment concerns the experimental design. The specific choice of design depends strongly on the objectives of the investigation, laboratory facilities, cost, available time, etc. E.g. the amount of randomisation nessesary to ensure unbiased results will influence the final design. The experimental design is closely related to the statistics used to evaluate the experimental results. The reader is referred to one of the many testbooks on experimental design, e.g. ref. [14]. Experimenters must ensure that data fulfil the requirements for a specific statistical analysis. Otherwise such analysis may lead to very erroneous conclusions, ref. [15]. It is worth to discuss the experimental design with a statistician before the experiment is started.

5. FINAL REMARK

It is well-known that great variance among observers must be expected in psychoacoustic investigations. It is less well-known that also different laboratories performing essentially the same investigation may come to different results. This was a surprising effect of an international investigation on impulsive noise comprising 21 laboratories all over the world, ref. [16]. It has not been possible to refer this "laboratory effect" to any errors in experimental design or the like.

Thus it must be expected that there permanently will be enough material for discussion among research workers within the field of psychoacoustics.

6. REFERENCES

[1] Baird,J.C. & Noma,E.(1978): Fundamentals of scaling and psychophysics. J.Wiley & Sons, New York.

[2] Guildford,J.P.(1954): Psychometric metods. McGraw-Hill, New York, London.

[3] Scharff,B.(1961): Loudness Summation under masking. J.Acoust.Soc.Am., vol.33, p.503-511.

[4] Stevens,S.S. & Poulton,E.C.(1956): The estimation of loudness by unpracticed observers. J. Exp.Psychol., vol.51, p.71-78.

[5] Levitt,H.(1971): Transformed Up-Down Methods in Psychoacoustics. J.Acoust.Soc.Am., vol.49, p.467-477.

[6] Levitt,H.(1978): Adaptive test in Audiology. In "Sensorinenral hearing impairment and hearing aids". (eds. C.Ludvigsen & J.Barfod). Scand.Audiol.Suppl. 6.

[7] Campbell,R.A.(1963): Detection of a Noise Signal of varying Duration. J.Acoust.Soc.Am., vol.35, p.1732-1737.

[8] Lyregaard,P.E. & Pedersen,O.J.(1971): Application of a digital computer for subjective measurements. Proceedings of 7th ICA, Budapest, vol.3, p.669-672.

[9] McNicol,D.(1972): A primer of signal detection theory. George Allen & Unwin, London.

[10] Engen,Trygg(1972): Scaling Methods. In "Woodworth and Schlosberg's experimental psychology", vol. 1. (eds.: J.W.Kling & L.A.Riggs). Holt, Rinehard and Winston,New York.

[11] Broadbent,D.E.(1979): Human Performance and Noise. In "Handbook of noise control" (ed.: C.M.Harris). McGraw-Hill, New York.

[12] Poulsen, T.(198x): Loudness of tone pulses in free field described by time constants. J.Acoust.Soc.Am.(Accepted for publication).

[13] Jacobsen,T.(1978): Measurement and Assessment of Annoyance of Fluctuating Noise. Report No.24, The Acoustics Laboratory, Technical University of Denmark.

[14] Cochran,G. & Cox,M.(1962): Experimental designs. John Wiley, New York, London.

[15] Abildgaard,F.(1973): On the damaging effect of neglecting some basic requirements in statistical analysis. Proceedings, Inter-Noise 73, Copenhagen, p.569-578.

[16] Pedersen,O.J., Lyregaard,P.E., Poulsen,T.(1977): The Round Robin Test on Impulsive Noise. Report No. 22. The Acoustics Laboratory, Technical University of Denmark.

Conference on
Low Frequency Noise and Hearing

7–9 May 1980
at Aalborg University Centre
Aalborg, Denmark
Proceedings edited by
Henrik Møller and Per Rubak

THE EFFECTS OF HIGH LEVEL INFRASOUND

DANIEL L. JOHNSON
Air Force Aerospace Medical Research Laboratory
Wright-Patterson AFB, Ohio 45433

INTRODUCTION

This paper will attempt to survey our current knowledge on the effects of relative high levels of infrasound on humans. While this conference is concerned mainly about hearing, some discussion of other physiological effects is appropriate. Such discussion also serves to highlight a basic question, "Is hearing the main concern of infrasound and low frequency exposure, or is there a more sensitive mechanism?". It would be comforting to know that the focal point of this conference is indeed the most important concern.

Therefore, besides hearing loss and auditory threshold of infrasonic and low frequency exposure, four other effects will be provided. These are performance, respiration, annoyance, and vibration.

AUDITORY THRESHOLD

A most common misconception about infrasound is that it cannot be heard. A glance at the results of various investigations[1,2,3] summarized in Figure 1 shows that infrasound can be heard (at least down to 1 Hz). Single frequencies of infrasound are not perceived as pure tones. Instead they are described as more of a chugging or motorboating sound. This leads one to the conclusion that what a person really hears is not a pure tone of infrasound, but instead the harmonics generated by the distortion from the middle and inner ear.

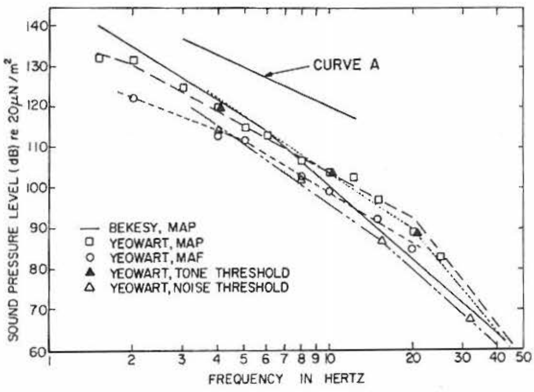


Figure 1. Hearing threshold levels for Minimum Audible Pressure (MAP), Minimum Audible Field (MAF), and for bands of noise. Curve A depicts the threshold of audibility due to middle ear distortion.

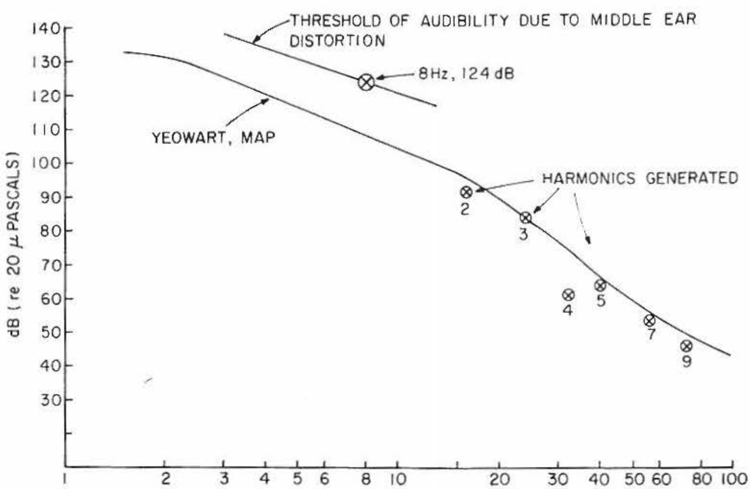


Figure 2. The Harmonics predicted due to middle ear distortion from a 8 Hz tone of 124 dB.

In our laboratory, we have investigated the possibility of known non-linearities of the middle ear causing infrasound to generate audible distortion. From just the middle ear non-linearities described by Kobrak[4], we can predict that infrasound should be audible by the time the levels reach the curve labeled A in Figure 1. For instance, a 8 Hz tone at 124 dB will produce harmonics due to the middle ear that lie on the audibility curve[5]. Figure 2 illustrates this example. Now if the audibility of infrasound is due to harmonic distortion, then it should be possible to mask the harmonics that are above 20 Hz. This is indeed the case. For instance a 7 Hz tone of 120 dB was easily masked in 5 out of 6 subjects if a 110 dB background noise (10-100 Hz) was presented[5]. A 10 Hz tone at 123 dB was detected by 3 of 6 subjects when it was added to the background noise shown in Figure 3. Often when analyzing noise in general, noise control engineers have blamed some bizarre effects on infrasound just because narrow band analysis showed that the highest Sound Pressure Level (SPL) was a narrow band in the infrasound region. The point I want to make here is that for most noises I'm aware of, it is not the infrasound that causes problems such as annoyance, chest vibration, etc., but audible frequencies about 20 Hz which are present in the noise.

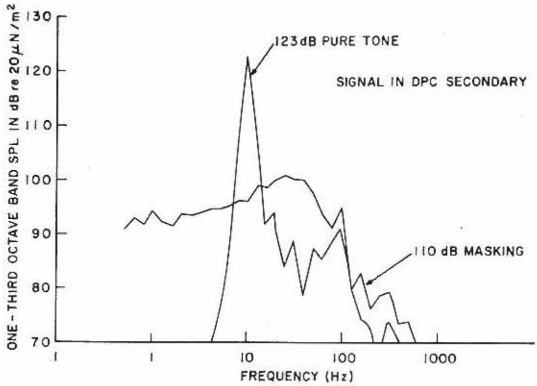


Figure 3. An overlay of both the one-third octave band analysis of a 110 dB background noise and a 123 dB 10 Hz tone. Only about one-half of the subjects could sense a difference between the combination of these noises and the background noise alone.

It can be noted that harmonic distortion could possibly cause levels of noise at higher frequencies that might be responsible for some Temporary Threshold Shift (TTS) at higher frequencies. This leads us into the next topic, the effect of infrasound on the auditory system.

HEARING LOSS

One of the more possible adverse effects of infrasound is the damage to the hearing organ. For exposures above 140 dB, TTS of the audiometric frequencies above 125 Hz of humans has been observed[6], although the frequencies above 1000 Hz seem to be the most sensitive. The TTS observed was usually small (less than 10 dB) and recovered rapidly. Figure 4 is a summary of results of various exposures to infrasound and the resulting TTS[6]. Recent whole body responses of 16 subjects to 142 dB at 7Hz for 15 minutes did not show statistically significant TTS.

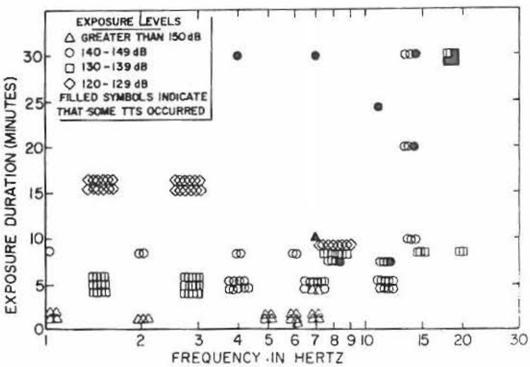


Figure 4. Conventional display of individual exposures recorded in our laboratory in terms of frequency and duration with levels as the parameter. Solid symbols indicate that some TTS was observed in the range of 125 Hz to 6000 Hz.

There is also the possibility of middle ear damage due to very intense infrasound. At 172 dB, exposures of 1 Hz (60 min), 4 Hz (15 min), and 8 Hz (7.5 min) all produced perforations of the tympanic membrane in chinchillas while exposures to 160 dB did not[6]. Histopathological investigation of the temporal bone of chinchillas exposed to such levels indicate major structural damage in the inner ear. Figure 5, prepared and interpreted by Dr. Lim of Ohio State University, illustrates such damage[7]. Endolymphatic hydrops and perforation of the saccular walls were common findings. This experiment has been repeated in greater detail and the final results will be reported this year. However, these structural changes seem to occur even at 160 dB, and the threshold of such effects may be as low as 150 dB for the chinchillas.

The chinchilla is probably more sensitive to infrasound than humans. There have been exposures of the auditory system in humans as high as 172 dB for less than 30 sec (1-8 Hz), 160 dB for 1 min (8 Hz) and 155 dB for several minutes (7 Hz). For these short times, no damage to the tympanic membrane or middle ear system occurred. However, the chinchilla results do indicate the need of caution in exposing humans to extremely intense (greater than 150 dB) levels of infrasound. This is in keeping with Tonndorf's reported scarring of the tympanic membrane of German submariners[8]. The exposure of men on snorkel subs constituted quite high infrasound exposures for long time periods. Unfortunately, the exact exposure level received by the men is unknown except that it is estimated to be considerably above 120 dB. It does not seem as clear to me as it has earlier, that the middle ear is the most sensitive part of the body. Nevertheless the middle ear certainly sets the physiological tolerance limit to infrasound due to pain. When we look at pain, we see that it is related to mechanical displacement of the middle ear system beyond its mechanical limits. Thresholds for pain as determined by Beksey and the Benox report[9] are summarized in Figure 4. There is some deviation in the data, but for the most part this depends on the type of stimulus used and interpretation of the sensations identified; the pain threshold, tickle threshold, or the touch threshold. Nevertheless, the pain threshold is probably the best indicator that we know at this time as to the physiological tolerance limit.

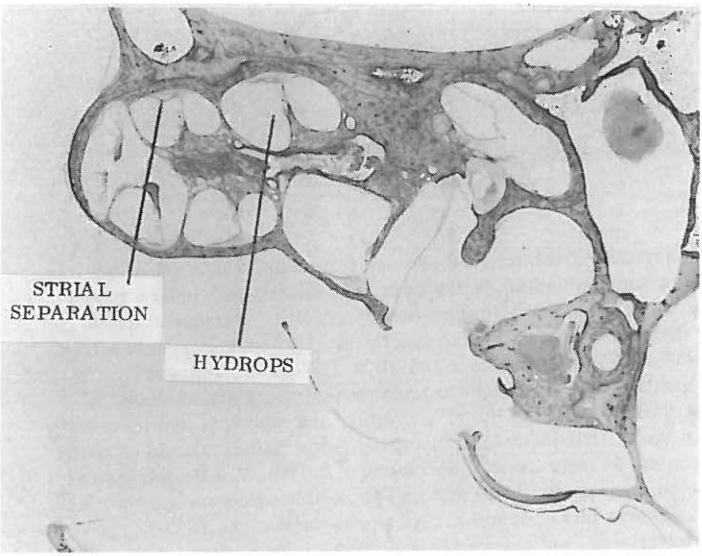


Figure 5. Structural changes due to exposure of 170 dB at 8 Hz for 10 min and 30 min exposures to levels of 153 dB to 166 dB from 12 to 30 Hz by Dr. Lim[7]

Also in Figure 6 is a range of the threshold of pressure buildup due to whole body exposures. This pressure sensation in the middle ear first starts from about 127 to 133 dB and is one of the most consistent findings in our infrasound exposures with humans [5,9,10]. The sensation does not necessarily become more intense as the SPL is raised and has been relieved temporarily by valsalva [10,11]. This pressure sensation can be explained in terms of a rectification effect caused by the eustachian tube and differs little from what one would feel during a 50 or 100 meter altitude change [12].

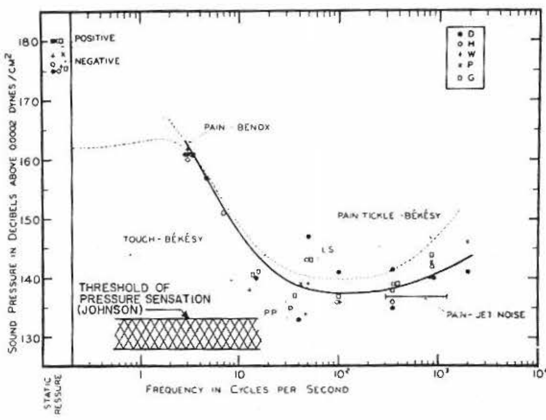


Figure 6. Thresholds of pain, tickle and pressure sensations.

PERFORMANCE

From the time Gavreau [13] first stated that weak infrasound could affect the balance or equilibrium mechanism in the ear, produce fatigue, induce nausea, etc., there have been a number of contradictory results. Various authors have suggested that infrasound can make you drunk [14,15] and adversely affect human performance. Even levels from 105 dB to 120 dB can supposedly affect reaction time, and thus are equivalent to a drunken state. Nevertheless, the experimentation done by Dr. Stan Harris, myself, and others in our laboratory during the past 6 years still indicates infrasound below 130 dB should be quite innocuous. The work by Borredon [16], who found a 130 dB, 7.5 Hz infrasound stimulus presented for a period of 50 min had negligible affect on human reaction time, also supports this contention. As I presented to the 1973 Paris Colluiquium on Infrasound, animal studies conducted in our laboratory yielded no results that would suggest any adverse effects at levels below approximately 160 dB [12,17]. Similarly, informal observations of human subjects exposed to infrasound suggested levels greater than 160 dB might be necessary to produce adverse effects. We then used nystagmography and a rail test of equilibrium to measure human responses to infrasonic stimulation objectively[18]. Nystagmus was not produced at intensity levels to 155 dB, and decrements in rail task performance were not observed at levels at 140 dB.

As these experiments did not absolutely prove that cognitive performance was not degraded, the cognitive performance of 40 subjects was measured by Dr. Harris during exposure to infrasound in three experiments[19]. In experiment 1, 12 subjects performed a serial search task while exposed for 15 min to each of four experimental conditions; 65 dB ambient noise, a low-frequency noise at 110 dB (see the 110 dB masking noise of Figure 3), a 7 Hz tone at 125 dB plus the ambient noise, and the 125 dB tone plus the low frequency noise. The second experiment was the same as the first except a Complex Counting Task was used and the exposure duration was increased from 15 to 30 min. In the third experiment eight female and eight male subjects were used. The Complex Counting Task was again used and the subjects were exposed for 15 min to 110 dB low frequency noise alone (see Figure 3) or with low frequency noise and 125 dB tone at 7 Hz, 132 dB at 7 Hz, or 142 dB at 7 Hz.

There were no decrements in performance revealed by analysis of variance in any of the three experiments. As with previous studies, there were no spontaneous comments from any of the subjects that would indicate they felt "drunk." Six subjects reported they were distracted by infrasound at the 142 dB level because of pressure in the ear, vibration, or inability to concentrate; however, corresponding degradation of performance was not measured for them as a group. It seems unlikely that any of these symptoms was caused by a direct stimulation of the vestibular system of our subjects, particularly, since there were no reports of vertigo, symptoms of motion sickness, or any illusionary movements of the visual field. While this experiment was not designed to note changes in auditory threshold, there was not statistical difference pre - post test thresholds in the normal audiometric range of 500 to 6000 Hz.

The lack of performance decrements from these experiments again support the contention that infrasound criteria proposed in the Paris Colloquium are reasonable[20]. There may be tasks that will show significant changes due to infrasound, but we have about given up looking for them.

RESPIRATION

One of the first studies accomplished by our laboratory was a short range program to confirm 140 dB would not jeopardize the mission of the crew of the Apollo rocket[11]. In the infrasound range, exposures of four experienced human subjects to discrete frequencies of as high as 151-153 dB were obtained for as long as 90 sec[11]. At these levels the subjects could feel the abdominal wall and chest wall moving. These sensations increased above 145 dB and at the 150-153 range the limit of voluntary tolerance was reached for the low frequency (above 10 Hz) exposures. This was due to the subject reporting a tickling and choking sensation in the throat, which led to the coughing response. The cause of this coughing reaction is most certainly the result of the oscillating air movement in the throat due to the pressure fluctuation. This air is undoubtedly drying the mucous membrane in this area, leading to tickling and choking sensations. This pressure oscillation can be increased such that infrasound can provide a means of artificial respiration. As I mentioned in the Colloquium at Paris, with the anesthetized animals respiration rate decreases once a SPL of 166 dB is reached. At 171 to 173 dB, respiration normally ceases for the larger dogs[12,21]. The explanation of this phenomenon is that air molecules are being exchanged between the ambient air and the lungs of the dog since each pressure fluctuation causes a density change of 10%. Thus infrasound at 172 dB serves to ventilate artifically the dog's lungs. The frequency range for which I have found this effect is 0.5 to 8 Hz, and it is interesting to note that below 1 Hz the chest is virtually motionless. This phenomenon was recently reverified for animals paralized with drugs; however, the practical use of this method of artificial respiration has not been developed.

ANNOYANCE

From a practical viewpoint, the greatest effect infrasound may have with respect to the general health and welfare is via all those many factors that make up the annoyance response. I am convinced people in general do not like to hear or feel infrasound. However, it is clear that infrasound should not annoy a person is it cannot be heard or sensed. Thus, the threshold curves of Yeowart should serve as the threshold of any human annoyance. Using this concept, a general annoyance criteria has been developed in Figure 7. The most sensitive curves of Yeowart are shown in Figure 1. Unfortunately, there are differences in the audibility of tones versus bands of noise as well as difference in Minimum Audible Pressure and Minimum Audible Field. Thus Figure 7 has a cross hatched range in which the infrasound may first be audible.

In keeping with the U.S. Environmental Protection Agency's suggested yearly Ldn of 55 dB as the value for audible sounds required to protect public health and welfare, it should be appropriate to equate the corresponding loudness curves for the Ldn of 55 dB to the loudness of infrasound. Whittle[22] et al, have the necessary loudness curves and the 45 phon curve (which is roughly approximate to an Ldn of 55) is estimated from their data. This is also drawn in Figure 7 for SPLs less than 120 dB. Note that there is relatively little difference between the threshold curves and the 45 phon equal loudness curve. This illustrates the fact, unlike noises in the 100 to 1000 Hz range, the effects of infrasound can go from absolutely nothing to quite severe with relatively little change in Sound Pressure Level.

However, there are other important factors which should serve as a rationale for limiting exposure of uncontrolled population to levels above 120 dB. The main consideration is with respect to the annoying rattling of buildings or even damage to such structures. It is interesting to note that around Cape

Kennedy, 120 dB was used as the upper limit for short term exposures of people or communites in the vicinity of the large rocket launch sites[23]. After 18 years of experience, this level seems to still be valid. Another reason for choosing 120 dB as the upper limit is the phenomenon of the middle ear pressure. The 120 dB value provides a 7 dB cushion against this disturbing phenomenon.

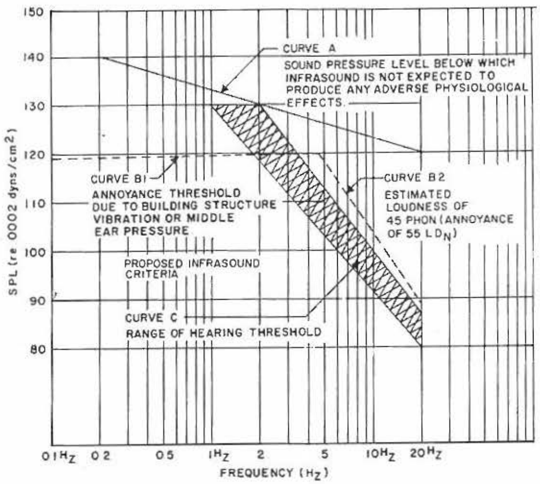


Figure 7. Various criteria proposed for infrasound exposure. Curve A first presented at Colloquium on Infrasound, Paris

In a recent CHABA publication, "Guidelines for Environmental Impact Statements,"[24] the infrasound limits for uncontrolled populations for 1 min or less was suggested as:

less than 120 dB. . . . . 0.1 Hz to 5 Hz

less than 120 dB - 30 log $\frac{f}{5}$ . . 5.0 Hz to 20 Hz

These levels are reduced by (10 log t) dB, where t is the total time and is between 1 and 100 minutes. Exposures longer than 100 min should use the 100 min limit. In other words, exposures 20 dB less than the 1 min criteria should be regarded as having no impact, regardless of exposure time. The 20 dB down point, incidently, basically insures that the infrasound is inaudible.

One practical method for reducing the annoyance due to infrasound was first suggested by Gavreau[13], and later by Westin[25]. Gavreau reported relief of the problems of infrasound was gained by masking the infrasound with high intensity sound such as music. This strategy certainly is in keeping with our experience that infrasound can be easily masked by higher frequency sounds. In fact, Figure 2 is a good example of such a strategy. Of course, care is required in order to insure the "cure is not worse than the bite."

VIBRATION FROM INFRASOUND

There are some definite similarities between whole body infrasound exposure and vibration exposure in that for both exposures it is the compressible air spaces which determine the resonances of the body. Although the force acts on all the body masses when sitting on a vibrating surface, it is the action of the abdominal mass, which moves in and out of the rib cage compressing the air in the lungs, which causes tolerance limiting resonance at 4 - 8 Hz[23]. Infrasound, because of the long wave length versus body size, acts uniformally on the whole body. Displacement of tissue primarily occurs if air is displaced or compressed, and the main air enclosures of importance in the body are the lungs and the middle ear. Low frequency sound and infrasound will act simultaneously on the abdomen, chest walls, and mouth, all of which will affect the lungs. This uniform pressure will cause the system to act much stiffer than if the stimulus is unidirectional vibration. This is why the main thorax/abdominal resonances to sound are in the 40 to 60 Hz range[23]. Such resonances have been measured by Leventhall[26] at Sound Pressure Levels as low as 105 dB, and if anyone sees the movie "Earthquake" (the Sound Pressure Level was measured as high as 120 dB in the 60 - 100 Hz region). The effect of such resonances are quite obvious. I would emphasize, however, that such resonances at these relative low sound pressure levels are in the low frequency range above 20 Hz, not in the infrasound range. Our experiments do indicate subjects do sense vibration of the abdomen or chest once the infrasound levels reach 132 dB or above in the frequency range of 4 to 20 Hz[10,19]. Interestingly, none of the four subjects exposed to 144 dB at 2 Hz or 1 Hz sensed any vibration.

CONCLUSIONS

This review emphasized those facts which, in my view, were the most pertinent. Fortunately, the present state of knowledge is more extensive than can be written in a few pages. The reader should be aware of other review articles, the better of which are the chapters of von Gierke and Parker, one of which is in a recent book on infrasound edited by Tempest[27] and the other in the Handbook of Sensory Physiology[28]. A review of the exaggerations of the effects of infrasound is provided by reference 29 while Westin provides a somewhat different viewpoint[25]. A short summary of the effects of infrasound is shown in Table 1.

Returning to the initial question concerning the importance of hearing loss from infrasound, the answer is a qualified yes. The auditory system does appear to be the most sensitive system with respect to direct physiological damage. Curve A of Figure 7 still seems reasonable, although I expect there is a moderate safety factor in this curve. However, exposures high enough to threaten the auditory system are somewhat rare. From the practical viewpoint, therefore, annoyance is the main factor that dictates permissible levels of infrasonic exposure. Unfortunately, little work has been accomplished on this problem. Our laboratory is continuing research on the effects of infrasound on hearing in the 150 dB to 170 dB range. I know of no one actively pursuing the annoyance question. In my opinion, annoyance provides one of the more timely research topics for infrasound.

AUDITORY THRESHOLD. . . .	Infrasound is audible down to 2 Hz, but loses tonal quality at 16 Hz. Infrasound is easily masked by low frequency noise.
HEARING LOSS	A small amount of TTS has occurred for exposures longer than 20 min, but generally a level below 150 dB is not expected to produce adverse results if exposure duration is less than 30 min.
PERFORMANCE	The threshold level of performance decrements has not been reached. No decrements, except for speech interference, have been found at levels below 142 dB.
RESPIRATION	Definite effect once 166 dB is reached. Artificial respiration can occur for .5 Hz - 8 Hz once 172-173 DB is reached.
ANNOYANCE	A definite problem. The threshold is probably the same level as the threshold of audibility.
VIBRATION	Approximately 132 dB from 4-20 Hz.
WHOLE BODY EFFECTS . . .	Start noticing adverse subjective effects past 150 dB. Tolerance limit not reached. Middle ear pressure buildup starts at 130 dB as well as voice communication modulation.

Table 1. Summary of thresholds where various effects should occur.

This paper is a compilation of AMRL-TR-76-17, AMRL-TR-77-51, and Research Memo, "Exposure of Four Chinchillas to Infrasound."

ACKNOWLEDGEMENT

Special thanks are due Alice Trnka for the typing and location of figures.

BIBLIOGRAPHY

1. von Bekesy, G. (1936), report in Experiments in Hearing, edited by E.G. Wever (McGraw-Hill, New York, 1960) pp 257-267.

2. Yeowart, N.S.; Bryan, M.; and Tempest, W. (1968). "Low Frequency Noise Thresholds," J. Sound Vib. 9, pp 447-453.

3. Yeowart, N.S., "Low Frequency Threshold Effects." Proceedings of Fall Meeting of British Acoustical Society 71.103, Nov 1971.

4. Kobrak, H.G., "Construction Material of the Sound Conduction System of the Human Ear," J. Acoust. So. Amer., 1948, 20, 125-130.

5. Johnson, Daniel L. and von Gierke, H.E., "The Audibility of Infrasound," presented at Acoustical Society of America Fall Meeting, Nov 1974.

6. Nixon, C.W. and Johnson, D.L., "Infrasound and Hearing," Proceedings of International Conference on Noise as a Public Health Hazard, Dubrovnik, Yugoslavia, May 1973. EPA Document 550/9-73-008, pp 329-347

7. Johnson, D.L., "Exposure of Four Chinchillas to Infrasound," Research Memo dated Mar 1976, AMRL, WPAFB OH.

8. Tonndorf, J., "The Influence of Service on Submarines on the Auditory Organ," Chapt, DH, Appendix to German Aviation Medicine in World War II, Dept of the Air Force, 1950.

9. von Gierke, H.E.; Davis, H.; Eldredge, D.H.; Hardy, J.D., "Aural Pain Produced by Sound," Benox Report, Contract N6cri-020, Task Order 44, ONR Project No. 144079, University of Chicago, Dec 1953.

10. Slarve, R.N. and Johnson, D.L., "Human Whole Body Exposure to Infrasound." Aviat Space Environ Med, 46(4): 428-431, 1975.

11. Mohr, G.C.; Cole, J.N.; Guild, E.; and von Gierke, H.E., "Effects of Low Frequency and Infrasonic Noises on Man." Aerospace Med, 36, 817-824 (1965)

12. Johnson, Daniel L., "Various Aspects of Infrasound," Proceedings of the Colloquium on Infrasound, Centre National de la Recherche Scientifique, Paris, Sept 1973.

13. Gavreau, V., "Infrasound," Science Journal, Jan 1968, pp 33-37.

14. Bryan, M., and Tempest, W., "Does Infrasound Makes Drivers 'Drunk'?" New Scientist, 1972, 16 Mar, pp 584-586.

15. Evans, M.J. and Tempest, W., "Some Effects of Infrasonic Noise in Transportation." Journal of Sound Vibration, 1972, 22 (1), 19-24.

16. Borredon, "Reaction Physiologiques De Sujets Humains Exposes A Des Infrasons," Centre de Recherches de Medecine Aeronatuique, Report 3713, Dec 1972.

17. Parker, D.L.; Ritz, L.A.; Tubbs, R.L.; and Wood, D.L., "Effects of Sound on the Vestibular System," AMRL-TR-75-89, Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, Ohio, 1976.

18. Harris, C.S.; Sommer, H.C.; and Johnson, D.L., "Human Equilibrium During Exposure to Infrasound." Presented at annual meeting of Aerospace Medical Association, San Francisco, 1975.

19. Harris, C.S., and Johnson, D.L., "Effects of Infrasound on Cognitive Performance," Aviat Space Environ Med, 49(4):582-586, 1978.

20. Roundtable Discussion Section, "Proceedings of the Colloquium on Infra-Sound," Centre National de la Recherche Scientifique, Paris, Sept 1973.

21. Johnson, Daniel L., "Effects of Infrasound on Respiration." Paper presented at Aerospace Medical Association Meeting, May 1973. Pages 37 and 38 of preprints of scientific program.

22. Whittle, L.D.; Collins, S.J.; and Robinson, D.W., "The Audibility of Low Frequency Sounds," Journal of Sound and Vibration, 21(4)431-448, 1972.

23. von Gierke, H.E., "Effects of Infrasound on Man," Proceedings of the Colloquium on Infrasound," Centre National de la Recherche Scientifique, Paris, Sept 1973, 417-435.

24. Guidelines for Preparing Environmental Impact Statements on Noise. Report of Working Group 69, H.E. von Gierke, Chairman, Committee on Hearing, Bioacoustics and Biomechanics, National Research Council, National Academy of Sciences, Washington DC, 1977.

25. Westin, J.B., "Infrasound: A Short Review of Effects on Man," Aviat Space Environ Med 46(9):1135-1140, 1975.

26. Leventhall, H.G., and Kyriakides, K., "Acoustically Induced Vibrations of the Body." Paper read at annual Conference of the U.K. Group on Human Response to Vibration, Yeovil, Sept 1974.

27. von Gierke, H.E. and Parker, D.E., "Effects of Intense Infrasound on Man," in Infrasound and Low Frequency Vibration, W. Tempest editor, Chap 6, Academic Press, New York, N.Y., 1976.

28. von Gierke, H.E. and Parker, D.E., "Infrasound," Handbook of Sensory Physiology, Vol V; Auditory System, Springer-Verlog, N.Y., 1976.

29. Harris, C.S.; Sommer, H.C.; and Johnson, D.L., "Review of the Effects of Infrasound on Man," Aviat Space Environ Med 47:430-434.

Conference on
Low Frequency Noise and Hearing

7–9 May 1980
at Aalborg University Centre
Aalborg, Denmark
Proceedings edited by
Henrik Møller and Per Rubak

PHYSIOLOGICAL EFFECTS OF INFRASOUND IN OUR EVERYDAY ENVIRONMENT

BORREDON P.
CENTRE D'ETUDES ET DE RECHERCHES DE MEDECINE AEROSPATIALE
5 bis Avenue de la Porte de Sèvres - 75731 PARIS CEDEX 15, FRANCE

ABSTRACT - The physiological effects of infrasound are considered from a very general point of view. The technical and methodological difficulties met in the study of these effects on man are underlined.

The effects of infrasound on performance are discussed.

I - INTRODUCTION

It is somewhat pretentious to try and describe in less than one hour the physiological effects of infrasound encountered in our usual environment. Two questions must be raised right away.

1 - Are there working places, leisure, or rest facilities, etc. where we are exposed to infrasound ?

2 - Are the encountered infrasound levels significant compared to the physiopathological effects which can reasonably be ascribed to infrasound ?

It is relatively easy to answer the first question as the literature abunds in data (1, 5, 7, 12, 13), and I believe Professor LEVENTHALL will give us valuable precisions in this area. In a first chapter of general considerations, after a review of a few definitions, I would say that there are more and more circumstances where man in our industrial society is exposed to infrasound.

It is, however, more difficult to answer the second question. As far as physiopathological effects ascribed to infrasound are concerned, it is a striking fact - as remarked by HARRIS, SOMMER and JOHNSON (9) - that scientific publications often use the style of tabloid literature. While enumerating the various effects (evidenced and presumable) of air transmitted mechanical vibrations on the human body, I will recall how difficult it was - even in the field of sound - to develop, on an international level, the protection standards to be applied in work or rest environments. I will then explain why it is so difficult to study the effects on man of such an environment factor as infrasound, on the one hand because of the *technical difficulties* inherent to its simulation in a laboratory and, on the other hand, because of the *methodological difficulties* which must be mastered when one wants to study the effects on man of one of the multiple physical factors making up his environment.

II - GENERAL CONSIDERATIONS

The term "infrasound" describes air transmitted mechanical vibrations with a frequency below 20 Hz. The vibrating material system is the gas molecule which oscillates within an elastic medium, the air. Each vibrating molecule transmits its vibrational energy to the neighboring molecules and the phenomenon is globally expressed as a function of time t, by a change in pressure ΔP (t) around the environning pressure, i.e. most often the atmospheric pressure P_{BZ}. At each instant, the pressure in one point is expressed by the relation :

$$P(t) = P_{BZ} + \Delta P(t). \qquad (1)$$

The pressure wave propagates through the air at a certain speed, velocity C. The velocity only depends on the considered environment ; it is independent of the frequency. The propagation speed of the infrasound pressure wave is therefore identical to the velocity of sound in the air at 20° C, i.e. approximately 340 m/sec.

The human body is provided with an air pressure differential transducer : the ear. This transducer is sensitive to ΔP (t) in equation (1). It is interesting to note that its pass-band is the criterion which was used to define the sound vibrations at frequencies ranging from 20 to 20,000Hz, the ultrasound with a frequency exceeding 20 kHz and the infrasound with a frequency lower than 20 Hz.

Aerial mechanical vibrations may be sustained or not. Non sustained or transient vibrations generally correspond to a large amplitude movement and the phenomenon only consists in a significant pressure variation wave which is rapidly dampened. Examples are given by sonic booms or fire arms. In the case of a sonic boom where the "N"-shaped wave lasts approximately 100 msec (fighter aircraft) to 300 msec (supersonic transport aircraft), the first terms of the Fourier spectrum are very significant and the infrasound spectrum components contain most of the energy. However, if the ultrasound is rapidly absorbed while propagating in the air, the same does not apply to low pitched sounds nor, *a fortiori*, to infrasound. Finally, at a great distance, the only persisting components of the spectrum are the infrasound.

As far as sustained vibrations are concerned, it is known that the evolution of technology,is such that the spectral distribution of the sound energies of many noise sources sinks more and more toward low frequencies. Closed - whether fixed or mobile - spaces which are ventilated by low-frequency pulsed air are in increasing number. Steel mills, cowpers, heavy duty diesel engines are all representative industrial sources of infrasound.

Finally, there are numerous natural (wind, thunder, earth-quakes, etc.) or technical sources of infrasound, and these few preliminary considerations show that wondering about the problems raised by the physiopathological effects of infrasound does not mean indulging in speculation. However, from such reflexions to the drive to explain the mysteries of the Bermuda triangle (11) or certain unexplained road accidents (4) by infrasonic influences, there is a step which should, perhaps, not be made.

III - EFFECTS OF AIR-TRANSMITTED MECHANICAL VIBRATIONS ON THE HUMAN BODY

Schematically, the physiopathological effects of air-transmitted mechanical vibrations may be considered under three aspects : energetic, informational and global, i.e. general effects.

III.1 - The *energetic effects* are encountered when the intensity of the sound stimulus is high enough to injure the cochlear sensor : this is the scene of occupational hearing loss. The consequences of exposure to very high level infrasound will be described by Daniel JOHNSON. However, may I be allowed to remark that even in the field of the effects of intense sounds, where the observer can use privileged exploration means such as audiometric systems, time was needed to agree on how to measure noise parameters and establish protection standards. In the case of industry-type noises, it is now unanimously agreed to measure an efficiency pressure integrated on a strandardized time interval (SLOW or FAST characteristic of sound meters) with decent weighting (dBA). However, the exposure time is still a matter for discussion. In France, the principle of equal energy is accepted, in other countries, reducing by half the exposure time allows a 5 dB and not 3 dB increase in sound level. In the case of impulse noises such as those made by firearms, we still have not come to complete agreement on the way to measure the physical parameters of noise and on how to consider these parameters to develop protection standards. I therefore believethat it will take a few more conferencesbefore the scientific community has a more uniform view on the physiological effects of infrasound, and all the more so as the first international symposium on infrasound was only held in 1973.

III.2 - *Informational effects* of sound vibrations are observed when the intensity of the sound stimulus is not dangerous for the cochlea. The sensor transmits the entire message to the higher integration centers. This influx of sensory stresses may have various effects : the operational message is mixed in and becomesless intelligible, or the only brain channel is saturated and the intellectual activity is impaired, or the sensory stress occurs unexpectedly, at night, for example, and sleep disturbances are observed. These few examples show that the informational effects can be assimilated to the concept of annoyance.

It is a very complex task to determine the sound levels which are likely to cause a feeling of annoyance. Some of the involved factors are : level, time history and spectral configuration of the noise ; informational contents of the noise ; individual factors such as sleep, work (task learning) rest, illness, etc. ; subjects personality ; psychosociological factors which can, themselves, be very changing.

To evaluate noise induced annoyance, it is therefore necessary to consider the problem not on an individual basis, but rather on the scale of a population. An epidemiological survey must then be conducted. However, if one wants to conciliate methodological rigor and multi-disciplinary data collection, such surveys are difficult to conduct and not very gratifying, on short term, for the operators !

In any case, in order that an informational effect can occur, the cochlear sensor must be stimulated in a pass-band and dynamics which are adapted. In the case of infrasound, which extends beyond the pass-band of the human ear, such a situation seems rather unlikely, and this is a good thing as the infrasound levels encountered in our everyday environment and expressed in dB (ref. 2.10^{-5} Pa) are relatively high (1,13).

III.3 - *General effects* : in the case of sound vibrations, these general effects are mixed, i.e. both energetic and informational with, most often, a frank predominance of the informational aspect. In the case of infrasound, however, the signal must always be energetic enough to allow these effects to occur. An audible air-transmitted vibration whose characteristics suggest that it will have essentially informational effects can, indirectly, by the intermediate of psychosomatic phenomena involve and disturb the major neuro-vegetative functions, which reflects a conflict in the structures of the central nervous system, between activation of sub-cortical structures (especially reticular) and inhibition of the cerebral cortex. GRANDJEAN's drawing (Fig. 1) perfectly illustrates this concept.

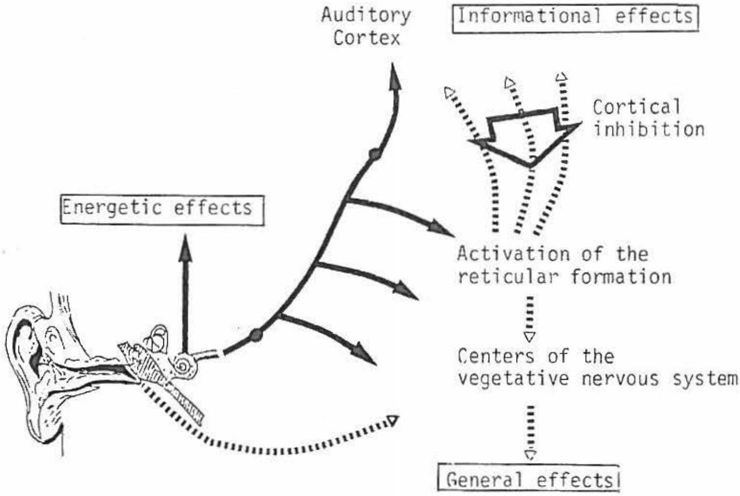


Figure 1 : The three aspects of noise effects on the human body (modified drawing, adapted from GRANDJEAN (8)).

Infrasound does not produce, on the efferent cochlear nervous paths, sensory information coded as bursts of action potentials. However, directly, the action on the eardrum of an air conducted vibration stimulus of sufficient intensity and low frequency can involve the sympathetic innervation of the middle ear. This potential situation must be taken into account, especially when the sound vibration is a very low frequency - maybe even an infrasound - which vibrates the eardrum without producing a specific auditory response, but rather a touch sensation which can bring discomfort or even be hazardous for a subject who previously had ear surgery (treatment for otospongiosis). Finally, it can be supposed that high amplitude infrasound fluctuations which cause significant pressure changes within the cochlear endolymph, can trigger an undesirable vestibular stimulation.

More directly still, the propagated infrasound vibration may directly act on all or part of the body, e.g. on the walls of the abdominal or thoracic cavities, or their air contents, or the organs suspended by their pedicles inside these cavities. It is known that, in man, the resonance frequencies of these elements lie in the infrasound range.

Finally, in the infrasound range, it is not obvious that the cochlear sensor be the system which, under stress, has the lowest response or injury threshold. It is, therefore, more difficult to investigate the physiopathological effects of infrasound than to study occupational hearing loss, for example, since in the latter the study of the cohclear response may be considered as comprehensive. However, in the case of infrasound, it does seem that the effects to consider are of a general type. Actually, when in a work environment people claim to be inconvenienced by infrasound, they essentially complain about a discomfort which evokes functional disorders in the major vegetative functions.

IV - STUDY OF THE EFFECTS OF INFRASOUND : EXPERIMENTAL FACILITIES AND METHODOLOGICAL PROBLEMS

A point should be immediately made concerning the experimental equipment which was used for biology experiments. This equipment practically always includes closed chambers in which a piston creates periodic pressure changes. An example is given by the experimental outfit that we used. It essentially consists in a rigid chamber (Fig. 2), one of the vertical walls including a movable panel driven by a hydraulic piston which imparts a sinusoidal movement to this panel.The chamber inner volume is approximately 6.3 m^3 (hexagonal shape ; 1.10 m wide x 2 m high walls). A speaker is mounted above the movable panel in a second opening in the back wall of the chamber. The hydraulic piston creates a change in the sinusoidal infrasound frequency pressure inside the chamber. The study of the spectral distribution of pressures investigated in thirds of octave shows the clear emergence of the basic infrasound signal in contrast to the accompanying harmonic spectrum (Fig. 3). Nevertheless, the interfering sound spectrum linked to the harmonic distorsion might contribute, to a great extent, to the subjective impression felt by the subject. A *counter-test must therefore be performed* and the loudspeaker recreates, in the chamber, an acoustic environment identical to the previous one but without its infrasound basic component. The absence of such a placebo treatment might falsify the result analysis as we already underlined it several times (2, 3).

Such facilities as the *Langley low-frequency noise facility* (9) or the *dynamic pressure chamber* of the Aerospace Medical Research Laboratory in Wright - Patterson AFB (USA) perfectly simulate pressure changes related to infrasound. However, it shoud be noted that the pressure and vibration velocity of particles are only in phase at a distance from the source equal to a wavelength.Therefore, such facilities do not simulate the low-frequency *vibrational energy flux* propagated in the air as can be encountered in nature or at certain work stations. In the interpretation of results obtained using these facilities, the question may be raised as to whether the effect of infrasound could not be partly related to the vibrational energy flux encountered and potentially absorbed by the subject. It should be noted, however, that for a 10 Hz frequency, the wavelength $\lambda = C/f$ is approximately 34 m, which evidently creates problems for the construction of an experimental system capable of accommodating a human subject. In addition, the poor

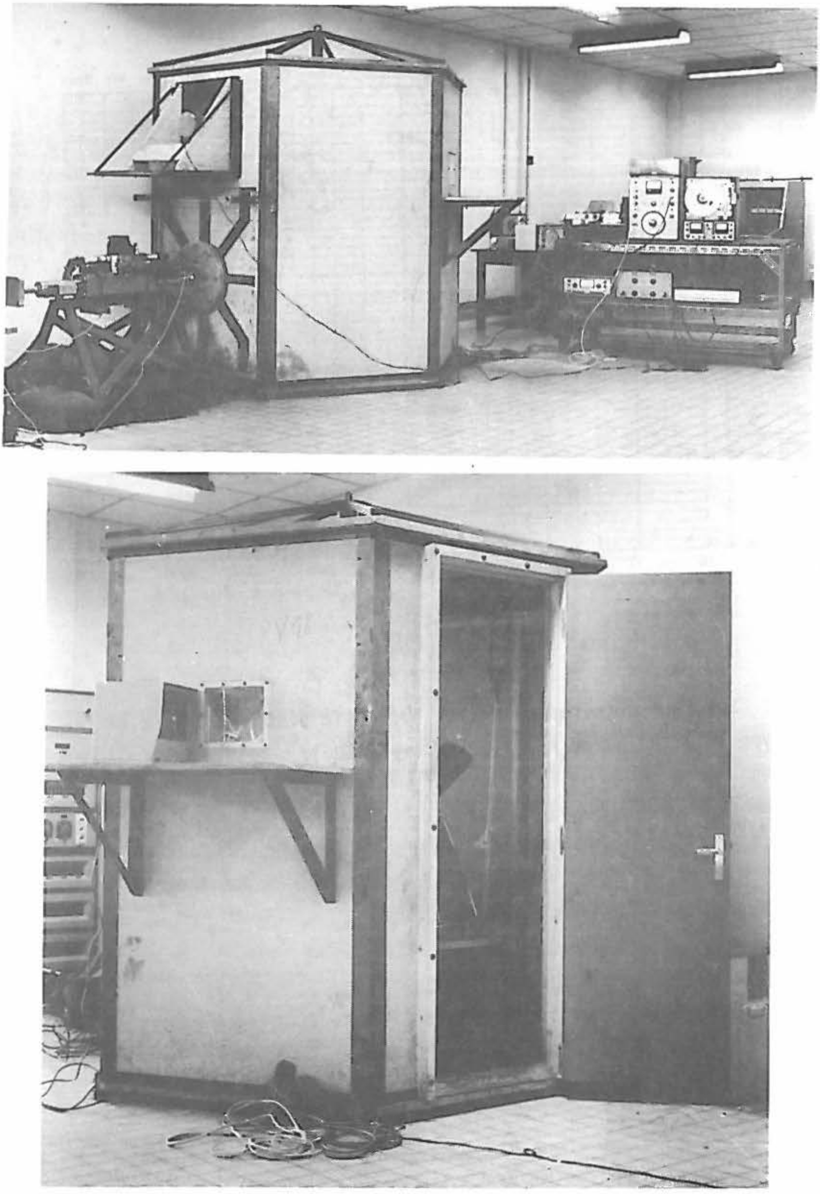


Figure 2 : Infrasound chamber used by the Centre d'Etudes et de Recherches de Médecine Aérospatiale (C.E.R.M.A.)

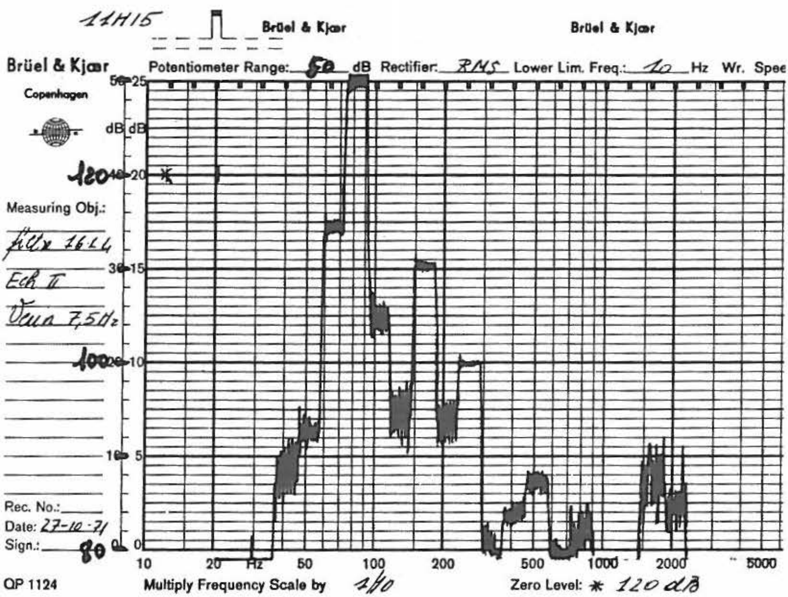


Figure 3 : Spectrum obtained using the hydraulic piston (B and K filter, type 1614 and B and K amplifier type 2606).

output of technical infrasound emitters must be taken into account. From this standpoint, Prof. GAVREAU designed good simulators but with a small diameter (6).

A final remark should be made concerning the use of experimental facilities or the information collected at certain work stations. It is obvious that the experimental or industrial sources of infrasound vibrate the solids which support them : floor of the workshop or walls of the experimental chamber. The subject whose reactions are observed risks being stressed by infrasound frequency vibrations which reach him, partly by solid transmission (floor-feet, for example), partly by aerial transmission. The energies involved in these two transmission modes are not generally comparable. In the case of solid transmission infrasonic frequencies, the problem is one of tolerance to vibrations. Only the effects of air propagated mechanical vibrations are considered here.

Similarly, when information is collected at a work station, it is obvious that the considered factors are most often quite intricate : an overall ergonomic analysis of the work station usually permits ascribing the felt discomfort to factors other than the originally incriminated infrasound factor.

V - THE EFFECTS OF INFRASOUND ON PERFORMANCE

The deterioration of performance under the effect of infrasound levels generated by vehicles seems to be a practically unanimously accepted fact. For example, a 115-120 dB infrasound level (Fig. 4) generated in road vehicles would increase the driver's response time by 30 to 40 % and make him drowsy, such effects being comparable to those of slight alcohol intoxication (1, 13).

As it is impossible to list here all the physiological effects which have been attributed to infrasound (3), I will only discuss one particularly dramatic effect.

We exposed forty-two young men for 50 minutes to sinusoidal changes in air pressure at 7.5 Hz and 130 dB (2). A relaxation chair was placed inside the chamber, it rested on a platform suspended by four rubber springs from the chamber ceiling. Using this system, the subject

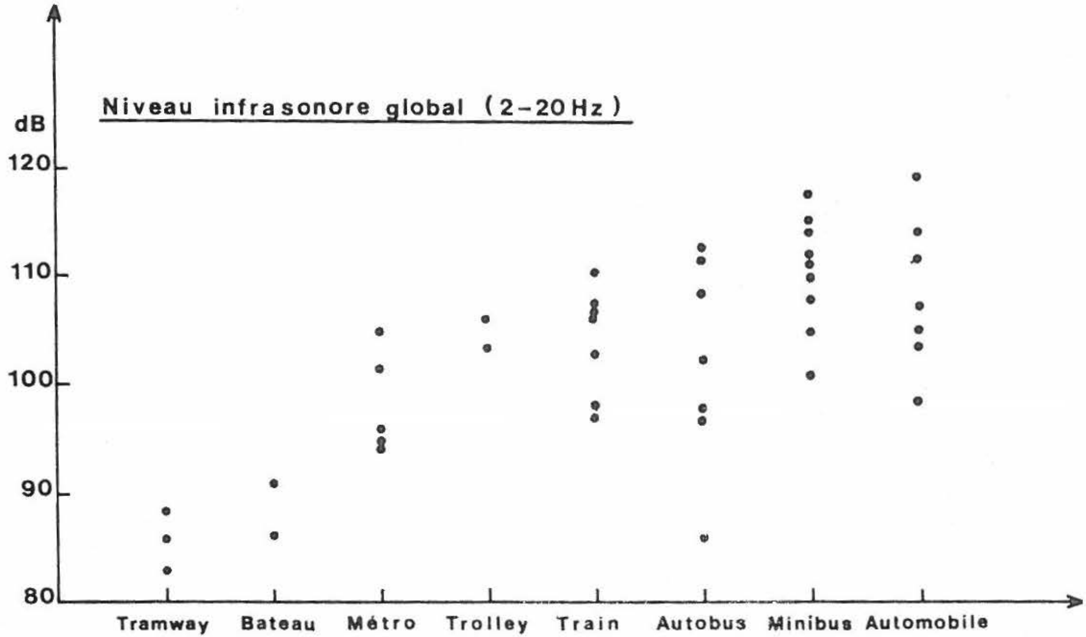


Figure 4 : Global infrasound level of noise generated inside various transportation means - From BONNARDEL G. (1).

was isolated from vibrations transmitted through the floor and only exposed to air vibrations. Sitting in the chair, the subject turned his back to the movable panel and could see perfectly well the chronoscope display. Each individual was exposed to three noise levels :

- *infrasound* : infrasound stimulus with its harmonic spectrum (piston working)
- *noise* : harmonic spectrum without its basic infrasound component (restored by the loudspeaker)
- *silence* : background sound level of the chamber (< 50 dBA).

It was important that the experimental subjects not consider the *infrasound* exposure as the privileged experimental phase. This is why it was impossible to use the laboratory personnel for this experiment. The subjects, all naive, unpaid volunteers were recruited outside the laboratory. In addition, great care was taken to make sure the experimental environment remained identical under the three test conditions (infrasound, noise, silence).

Each subject was exposed for 50 minutes to each one of the three conditions, randomly, but in an order equilibrated in a 3 x 3 Latin square design. The experiment was repeated according to the method of separate squares until 14 randomized Latin squares were completed (i.e. 42 subjects). Each subject was exposed to three experimental conditions in the same week, always in the morning. We know, and it was verified, that for a given subject, there is a relationship between a measure obtained for instance, during exposure to infrasound and that obtained before such an exposure. This is why we used a covariance analysis, comparing *among themselves* the mean values measured under the experimental conditions, taking into account the values measured before exposure (to infrasound, noise or silence).

The mean response time to a light stimulus was measured using a digital display electronic chronoscope. 16,128 elementary response times were determined. Each measure is, in fact the mean of 32 elementary times corresponding to 32 successive randomized displays within a 2 1/2-minute display cycle. A cycle is preceded by a state of alarm (the light is turned off in the chamber).

The independent variate is the result of a measure made 10 minutes before exposure to infrasound (or noise or silence). The dependent variate is the mean of 3 measures made respectively 15, 30 and 45 minutes after the beginning of experimental exposure. The following results were obtained (adjusted means) :

Response time during infrasound exposure = 0,2465 s.
Response time during noise exposure = 0,2493 s.
Response time during silence exposure (< 50 dBA) = 0,2482 s.

The three tested differences are respectively the comparisons : infrasound/noise (natural action of the infrasound), noise/silence (natural action of the low pitched sound area of the spectrum), infrasound/silence (effect of total spectrum). None of these differences is, of course, significant, and yet, the sound level is 130 dB on the I/3 of octave filter centered on 8 Hz !

It must be noted that during exposure to infrasound, our subjects exhibited slight drowsiness, as they were rocked in the relaxation chair by the monotonous rhythm of the infrasound pulse which is quite similar to that felt in the cabin of a ship driven by diesel engines. And still, their response time to a light stimulus measured *after preliminary alarm* was not changed at all, which proves that, in itself, infrasound exposure had absolutely not deteriorated their alertness, contrary to what happens under the effect of alcohol.

Under these conditions, it does not seem reasonably possible to make the infrasound levels usually found in our general environment, and particularly those generated in transportation means, responsible for such a fantastically negative impact on performance as was thought by some authors. However, in an experiment conducted with methodological rigor KYRIAKIDES and LEVENTHALL (10) succeeded to show, in a complex task completion test, a very slight deterioration of performance, with time, under infrasound exposure (115 dB LIN between 2 and 15 Hz). Therefore, the question is still pending. It simply seems that if infrasound had all those frightening powers described by some authors, all diesel car drivers or those people who dare drive with their windows open would never make it to where they are going !

ACKNOWLEDGEMENTS

The author gratefully thanks Mrs. D. Freund for the English translation of this text, and Mrs. S. Baldacchino for the typing.

REFERENCES

1 - BONNARDEL G., Les infrasons et les transports.
Institut de Recherche des Transports - Rapport IRT n° 24
BRON, 1977 (80 p).

2 - BORREDON P., NATHIE J., GIBERT A., Etude chez l'homme, des effets physiologiques d'une exposition à des niveaux infrasonores de 130 dB, Pages B 28, 1-13, in von GIERKE H.E., Vibration and combined stresses in advanced systems, AGARD - CP n° 145, 1975 (Purchase agency : NTIS).

3 - BORREDON P., QUANDIEU P., Considérations actuelles sur les effets physiopathologiques des infrasons.
Radioprotection, 1977, 12 (n° 4) 345-357.

- BRONER N., The effects of low frequency noise on people-a review.
J. Sound. Vib., 1978, 58 (n° 4), 483-500.

4 - BRYAN M., TEMPEST W., Does infrasound make drivers "drunk" ?
New scientist, 1972, 53, 584-586.

5 - Colloque international sur les infrasons n° 232
Editions du CNRS - PARIS 1974 (435 p).

6 - GAVREAU V., CONDAT R., SAUL H., Infrasons : générateurs, détecteurs, propriétés physiques, effets biologiques. Acustica, 1966, 17, 1-10.

7 - Von GIERKE H.E., PARKER D.E., Infrasound p. 585-624 in KEIDEL W.D., NEFF W.D., Handbook of sensory physiology Vol. V/3
Auditory system clinical and special topics, Springer-Verlag
BERLIN, 1976, (811 p).

8 - GRANDJEAN E., Précis d'ergonomie. Organisation physiologique du travail.
Dunod éd. PARIS 1969, (275 p).

9 - HARRIS C.S., SOMMER H.C., JOHNSON D.L., Review of the effects of infrasound on man.
Aviat. Space Environ, Med., 1976, 47, (n° 4), 430-434.

10 - KYRIAKIDES K., LEVENTHALL H.G., Some effects of infrasound on task performance.
J. Sound. Vib. 1977, 50 (n° 3), 369-388.

11 - KRAVTCHENKO A., On suspecte les infrasons.
Revue Militaire Soviétique, 1975, n° 10, 28-29.

12 - PIMONOW L., Les infrasons.
Editions du CNRS - PARIS 1976 (277 p).

13 - TEMPEST W., Infrasound and low frequency vibration,
Academic Press, LONDON, 1976 (364 p).

Conference on
Low Frequency Noise and Hearing

7–9 May 1980
at Aalborg University Centre
Aalborg, Denmark
Proceedings edited by
Henrik Møller and Per Rubak

Psychological, Ergonomical, and Physiological Effects of Long-term Exposure to Infrasound and Audiosound

H. Ising, Institute for Water, Soil, and Air Hygiene
Federal Health Office, Berlin
Postbox D 1000 Berlin 33

Summary

The concept and first results of a series of three studies of noise effects in men are reported. A total of nearly 100 volunteers was tested under control and different low frequency and audio frequency noise situations for up to 10 days. No specific infrasound effects (i.e.giddiness or nystagm) could be detected. We found, however, stress effects under infrasound exposure (110 dB, three octave bands between 3 and 24 Hz) similar to audiosound.

Exposure room [1]

In our exposure room, two test persons worked for 8 h/d. Low frequency sound in the range between 3 and 24 Hz was generated by 24 loudspeakers mounted in one wall of the room. During exposure the tilting window was kept open.The sound pressure level in most of our low frequency experiments was 110 dB. Audiosound was generated in the same room by means of a wide-band loudspeaker combination.

1. Pilot study

The following exposure parameters were chosen:
pure tones and 1/3 octave band noise; frequency range: 5-20 Hz. Infrasound pressure field: level range: 100-125 dB
Infrasound pressure gradient field: level range: 80-130 dB/m
Earphone [1,2] pure tones 4-20 Hz
In-phase and anti-phase 130-140 dB

A total of 12 test persons was exposed to certain of these conditions for up to 4 h. 28 test persons, mostly students working on self-chosen subjects, were exposed to 110 dB, 12.5 Hz, 1/3 octave band noise for 8 h, and control conditions for the same time.

We did not find any specific infrasound effects in man, especially neither giddiness [3] nor nystagm [2]. We found, however, stress effects of infrasound which were qualitatively similar to the extraaural effects of audiosound. About 50 % of our test persons felt disturbed and showed slight increases in systolic blood pressure and heart rate variation as well as decreases in finger pulse integral values [4,5].

The aim of the ensuing parts of our study was to compare the stress effects of infrasound and audiosound and to study the frequency dependance of infrasound effects. We decided to test each person for 10 days each under various low frequency, audiosound, and control situations. Therefore, the number of test persons had to be restricted. In order to select a nearly homogeneous group in respect of noise sensitivity, we performed the second part of our study before we started the final part with 10 test days for each person.

2. Audiosound study

57 voluntary male test persons aged between 18 and 34 (aver-

age of 24 years) worked alternatively on one day without traffic noise and on one day with traffic noise, at a constant equivalent noise level of 85 dB (A). On the first day, one half of the group worked with, and the other half without noise. After a short instruction, all test persons welded simple electronical circuits according to a given model. The total numbers of correctly welded electronical circuits were taken as a standard of achievement, and the faulty circuits as a failure standard.

The first morning, each test person completed a questionnaire in order to evaluate the subjective sensitivity to noise. The psychical state between the poles, tension - placidity, of the test persons was measured by questionnaires on both days at midday. The questions "Do you feel: - tensed - discontented - irritable - restless - stirred up - able to concentrate?" were answered on a 5-grade scale and summarized to measure the psychical state. Pulse frequency and blood pressure were taken each hour (Stereocard, Dr. Lange, Berlin) from 50 of these test persons.

During the working period, urine was continuously collected for the analysis of epinephrine, norepinephrine, and cAMP, and after work, blood samples were taken on both days for the analysis of Ca, Mg, Na, protein, cholesterol, and renin.

In Table No. 1 changes in the averages of performance, circulation, and biochemical parameters over working periods of 7 1/2 h are given, together with acute values of changes of the psychical state and the changes of the blood parameters.

In the four different fields of psychical reactions, performance, blood circulation, and biochemistry, we could establish obvious effects of traffic noise.

In order to describe the associations between sensitivity to noise and some objective parameters, Spearman rank correlation coefficients are reproduced in Table 2.

In our spot checks, these correlations demonstrated the presence of

1. an increase of sensitivity to noise with increasing age;
2. an increased blood pressure with increasing sensitivity to noise;
3. an increase in sensitivity to noise as well as changes of tension under noise stress with decreasing magnesium content of the erythrocytes (eMg);
4. an increase of psychical tension, a decrease of the quality of work, and an acceleration of the heart frequency under noise stress.

In Table 3, correlation coefficients between noise-induced changes of parameters from the fields of psychical reactions, performance, blood circulation, and biochemistry are given. The results evaluated either referred to the total group or the 28 test persons who according to the questionnaire were most sensitive to noise.

These correlations were

1. For the entire group, an association between psychical tension through traffic noise and increases of heart frequency and blood pressure.

2. The decrease of working quality under the influence of noise which was established for the total group, was associated with changes of electrolytes in serum and with an increase of the heart frequency in the noise-sensitive subgroup. In this sub-group, the association between increased release of epinephrine and an increase in blood pressure under noise stress became evident.

Our results have demonstrated -

1. the suitability of our questionnaire for the identification of noise-sensitive test persons;
2. the usefulness of our method and the chosen parameters for a noise effect study;

3. the interaction of psychical, ergonomical, physiological and biochemical parameters under noise stress.

According to the results of part 2, we tried to select a homogeneous group of 18 test persons for the intensive low-frequency study in part 3. Because of the long test period of 10 days per person, however, we could not find enough volunteers with high sensitivity to noise. Therefore, we had to accept persons with less sensitivity to noise as well.

3. Low frequency and audiosound study

18 test persons worked for 10 days each, mostly on electronic circuits. The first day was used for adaptation. In the following 9 days, 3 control situations and 6 noise situations were arranged together with the 9 groups of 2 test persons to form a Latin square. Thus, we excluded the influence of sequence.

The noise conditions were:

1.	low frequency octave band noise	3-6 Hz, 110 dB
2.	" " " " "	6-12Hz, 110 dB
3.	" " " " "	12-24Hz, 110 dB
4.	audiosound (tape-recorded traffic noise).	75 dB (A)
5.	" " " " "	75 dB (A)
6.	a combination of 2. and 4.	

The test parameters were:

1. efficiency and quality of work
2. psychical state
3. reaction time
4. ECG, heart frequency
5. temple pulse
6. pulse wave velocity (from 4 and 5)
7. respiration frequency
8. blood pressure
9. epinephrine) from the urine,
10. norepinephrine) collected over 7 1/2 h
11. cAMP)

Working parameters, psychical state, blood pressure, and biochemical parameters were measured similarly to part 2, only the frequency of blood pressure measurements was increased to 3 times per h. At the same frequency, the reaction time was measured. The physiological parameters 4.-7. were measured by an automatic device. The time interval between the ECG R-wave and the steepest slope of the temple pulse was converted into an analogous voltage which was reciprocal to the pulse wave velocity.

A computer (HP 9815)-controlled switch was installed between the measuring amplifier (Siemens) and the ECG electrodes, the photoelectric pulse pick-up, and the thermistor respiration pick-up on both of the test persons of each group. The computer controlled an alternating sequence of the two test persons with a duration of 9 min (measuring period) and 1 min (switching period), respectively. During the 9 min measuring period the 3 outputs of the measuring amplifier as well as a voltage reciprocal to the pulse wave velocity were measured by a digital voltmeter (HP-3437A) and a scanner (HP-3495A) once per s. The computer calculated the mean values and standard deviations of each parameter and stored these values in a cartridge tape unit (HP-9875A). At the end of each test day, the blood pressure values were stored as well. The time dependencies for all the physiological parameters over a day were plotted by a printer-plotter (HP-9871A). At the end of the experimental part of this study, the physiological data were transferred on punch tape by a Facit (6075/70) for statistical analysis in the central computer of the Federal Health Office. The ergonomical, psychical, and biochemical parameters were manually transferred to the central computer.

As a first result we found a statistically significant (Friedman test) increase of psychical tension: starting with control situations, over the infrasound conditions with increasing frequency and traffic noise to a combination of infrasound and audiosound.

Table 1: Changes of the specified parameters in 57 test persons during 7 1/2 working hours under traffic noise (Leq = 85 dB (A)) as compared with work without noise (Leq < 50 dB(A)).

Psychological parameters	Psychical tension	0.5 grades on a 5 grade scale +++
Performance parameters	Total achievement	+ 12 % ++
	Total failures	+ 29 % ++
	Quality	- 5 % ++
Blood circulation parameters	Pulse frequency	+ 26/min ++
	Systolic blood pressure	+ 3 mm Hg +++
	Diastolic blood pressure	+ 2 mm Hg ++
Biochemical parameters	Epinephrine	+ 33 % ++
	Norepinephrine	+ 7 %
	cAMP	+ 4 % +
	Serum - Mg	+ 3 % ++
	Erythrocyte - Na	- 6 % +++
	Total protein	+ 2 % ++
	Total cholesterol	+ 2 % +
	Renin	- 16 % +++

Levels of significance (Wilcoxon test) -

+ = 5 %; ++ = 1 %; +++ = 0.1 %

Supported by
Minister für Forschung und Technologie,
Programm: Humanisierung des Arbeitslebens.

Table 2: Rank correlation coefficients r_s, personality characteristics, and changes in tension against objective parameters, and their changes under traffic noise (Leq = 85 dB(A) compared with quietness (Leq $<$ 50 dB(A)

Sensitivity to noise	/ age	$r_s = 0.34^{++}$
	/ diastolic blood pressure	$r_s = 0.34^{++}$
	/ e-Mg	$r_s = -0.33^{+}$
	/ increase of psychical tension	$r_s = 0.36^{++}$
	/ decrease of work quality	$r_s = 0.32^{++}$
	/ increase of heart frequency	$r_s = 0.32^{++}$
Noise-induced increase of psychical tension	/ e-Mg	$r_s = -0.31^{+}$
	/ cAMP	$r_s = -0.35^{++}$

Table 3: Rank correlation coefficients r_s between noise-induced changes of psychical, ergonomical, physical, and biochemical parameters

Entire group

Increase of psychical tension	/ increase of heart frequency	$r_s = 0.44^{+++}$
	/ increase of the diastolic blood pressure	$r_s = 0.36^{+}$

Noise-sensitive sub-group

Decrease in quality of work	/ increase of serum Ca	$r_s = 0.46^{++}$
	/ increase of serum Mg	$r_s = 0.37^{+}$
	/ increase of heart frequency	$r_s = 0.38^{+}$
Increase of epinephrine excretion	/ increase of diastolic blood pressure	$r_s = 0.50^{++}$

References

[1] Ising, H., B. Shenoda, C. Wittke; Acustica 4/43 (1980)

[2] Evans, M.J., W.Tempest; J. Sound Vibr. 22 (1972),19

[3] Brüel, P., H.Olsen "Internoise 72" Kopenhagen (1973)

[4] Ising, H. u. C. Wittke Proceedings of the Institute of Acoustics, London (1979)

[5] Ising, H. u. C. Wittke Forum Städtehygiene 30(1979)49

Conference on
Low Frequency Noise
and Hearing

7–9 May 1980
at Aalborg University Centre
Aalborg, Denmark
Proceedings edited by
Henrik Møller and Per Rubak

THE INFLUENCE OF INFRASOUND ON TASK PERFORMANCE.

Henrik Møller
Institute of Electronic Systems
Aalborg University Centre
Postbox 159, DK-9100 Aalborg
Denmark.

Summary.

16 subjects were exposed to infrasound and traffic noise while task performance measurements were carried out. Infrasound above the hearing threshold level (120 dB) seems to affect human task performance. An addition duty was carried out 7% slower, and the reaction time in a complex reaction time test was increased 6%. In a cue utilization test there were 80% more errors. Traffic noise at L_{eq} = 71 dB(A) showed no effects.

Introduction.

It has often been claimed that infrasound could influence human performance. Most observations of this kind are from human everyday environment, where both the exposure and the observation of the performance are uncertain. Therefore laboratory experiments are needed where the exposure is well known (infrasound without vibrations, audio frequency sound etc.), and where a number of well defined performance parameters are recorded. Experiments like these have been carried out [1-10] but the results are not very concordant, and further investigation is needed.

This investigation deals with both physiological parameters, task performance and subjective annoyance impressions, but only the task performance recordings have been analysed until now, and they will thus be the only subject of this paper.

Exposure.

The experiments were carried out in an infrasound test chamber built at Aalborg University Centre [11,12]. The chamber is rather large, 16 m^3, in order to avoid psychological reactions from the subjects. The infrasound is generated by 16 large electrodynamic loudspeakers. To allow experiments of long duration the test chamber is equipped with a ventilating system.

Four different exposures were used. In addition to two infrasound signals, a "quiet" exposure was used, and for comparative reasons, an audio frequency noise.

- A - quiet.
- B - traffic noise. This was a recording from a main road in Aalborg. The playback level was L_{eq} = 71 dB(A).
- C - low level infrasound, see figure 1. Total SPL=100 dB.
- D - high level infrasound, see figure 1. Total SPL=120 dB.

C and D were broadband infrasound signals, frequency shaped along the treshold curve 5-25 Hz, which makes the "low" and "high" frequencies equally audible. The total spectrum C is hardly audible, while D is subjectively loud.

Recordings of task performance.

9 different task performance measurements were used. The tests consisted of duties presented either on a small film viewer or on a CRT-display terminal. The duties were answer-

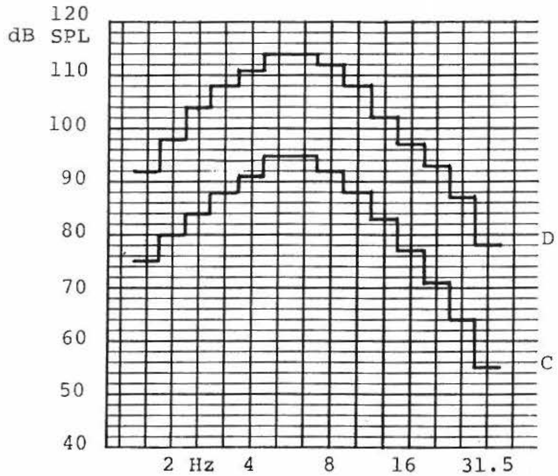


Figure 1.
1/3 octave analysis of the stimuli C and D.
Total SPL:
C: 100 dB
D: 120 dB

ed by pressing pushbuttons. Some of the tests were developed at The Laboratory of Heating and Air Conditioning at The Technical University of Denmark, where the purpose was measurement of task performance during exposure to different conditions of temperature, humidity of air and the like [13]. In the tests the answering of one duty was immediately followed by presentation of the next one.

Test 1 consisted of addition duties. 5 three-digit numbers should be added. Three suggestions of the sum were presented and the subject should choose between these or indicate, that none of them were correct. The four answers were equally probable.

In test 2 nine two-digit figures were presented and the subject should indicate whether they were all different. In 34% of the presentations two or more figures were identical.

In test 3 logical statements of a certain construction were presented. The subject should indicate whether the statement was right or wrong.

Exemples: A precedes B: AB (right)
After A is C: CA (wrong)
C does not follow B: CB (right)
A is not before B: AB (wrong)

Test 4 was a cue utilization test; a modified version of the Tsai-Partington test [14]. The order 1-A-2-B-3-C-4-D etc. should be followed, and the subject was to indicate whether the next sign could be found, see figure 2.

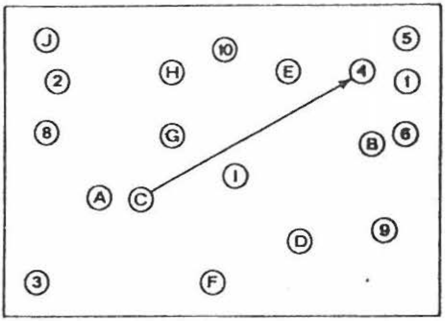


Figure 2.
Example of test 4.

Test 5 was a short time memory test. A list of words was presented, one word at a time. Each word might occur more than once and the person should indicate whether he had seen it before.

Test 6 was a simple reaction time test. When a letter appeared in the centre of the CRT display a pustbutton should be pressed. The time from answering to presentation of the next stimulation was random but uniformly distributed in the range 2-6 seconds.

In test 7 the display was divided into five parts and the letter E appeared in one of them every 2 seconds. The subject should react only on appearance in the centre.

In test 8 the display was divided into two parts by a vertical line. The letters E and F could appear one at a time at either the left or the right side. The subject should only react on an F to the left or an E to the right.

Test 9 was simular to test 2, but carried out with other equipment.

Experimental design.

15 young students and one person of 43 years were used as subjects, half of each sex. During two months they all participated in the experiment four days, each day for 4 hours. In a 4-hour setting 3 hours were used for exposure to one of the four conditions given above. The subjects participated two at a time and they were all exposed to all four conditions, although not in the same order. A latin square design was used in order to balance out learning effects, see table I.

	person number: 1-4	5-8	9-12	13-16
1. exposure:	A	B	C	D
2. exposure:	B	C	D	A
3. exposure:	C	D	A	B
4. exposure:	D	A	B	C

Table I. Latin square design of the experiments.

For each setting a strict time table was used, see figure 3.

Results.

From the tests were recorded mean response time and percents of errors (except test 6, where only the response time was recorded).

It is not surprising that the quantities differ strongly from person to person. Therefore all values are normalized, which means that they are divided by the total mean for the person in that particular test. For each sound stimulus mean values and standard deviations of the normalized variables are calculated. For the response times results are shown in figure 4.

<table>
<tr><th>Time:</th><th>Activities for the first person:</th><th>Activities for the second person:</th><th></th></tr>
<tr><td></td><td>audiometrical measurement</td><td>fixing electrodes etc. for physiological measurements</td><td></td></tr>
<tr><td></td><td>fixing electrodes etc. for physiological measurements.</td><td>audiometrical measurement</td><td></td></tr>
<tr><td>0h 00m</td><td>test 6, 7, 8, 9</td><td rowspan="3">test 1</td><td rowspan="12">sound stimulation</td></tr>
<tr><td></td><td>test 4</td></tr>
<tr><td>0h 30m</td><td>test 2</td></tr>
<tr><td></td><td colspan="2">measurement of blood pressure</td></tr>
<tr><td>1h 00m</td><td>test 3</td><td>test 6, 7, 8, 9</td></tr>
<tr><td></td><td>test 5</td><td>test 4</td></tr>
<tr><td>1h 30m</td><td>test 6, 7, 8, 9</td><td>test 2</td></tr>
<tr><td></td><td colspan="2">measurement of blood pressure</td></tr>
<tr><td>2h 00m</td><td rowspan="3">test 1</td><td>test 3</td></tr>
<tr><td></td><td>test 5</td></tr>
<tr><td>2h 30m</td><td>test 6, 7, 8, 9</td></tr>
<tr><td></td><td colspan="2">measurement of blood pressure
questionnaire for subjective impressions</td></tr>
<tr><td>3h 00m</td><td>audiometrical measurement</td><td>taking off electrodes</td><td></td></tr>
<tr><td></td><td>taking off electrodes</td><td>audiometrical measurement</td><td></td></tr>
</table>

Figure 3.
Time table for each 4-hour experiment.

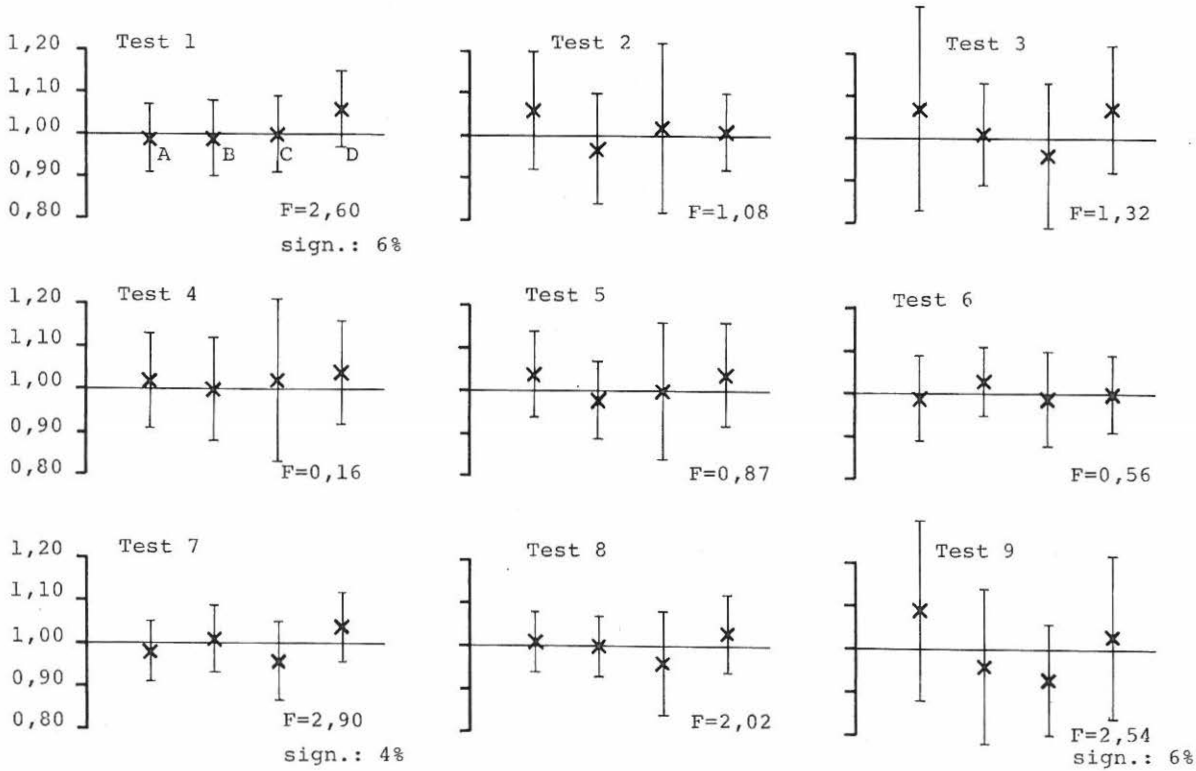


Figure 4. Mean values (x) and standard deviation (vertical bars indicate $\pm$ 1 s.d.) of the normalized response times. F values and significance levels: see text.

It is quite obvious that no general deterioration in the performance caused by the sound stimuli in B, C and D can be seen from the figure. According to the mean values, the subjects worked faster in some tests and slower in others, when exposed to noise.

Before making any conclusions about the influence of the noise on performance it is important to clarify whether the observed differences are so large that they cannot be explained as random. For this purpose a one way analysis of variance has been carried out. In this analysis the H_o hypothesis is: the mean values are all equal. The significance level indicates the probability of obtaining the observed results or values that differ even more if H_o were true. F values and significance levels from the tests are indicated in figure 4. In test 1, 7 and 9 H_o is rejected at 6%, 4% and 6% level, respectively. Only results from these tests are further analysed.

In simple t-tests the values from B, C and D are compared to values in A. The following is observed: Test 1: the response time is longer in D (significant at 2% level). Test 7: the response time is longer in D (3% level). Test 9: the response time is shorter in C (2% level).

The values of the error percents were analysed in a similar way. The analysis of variance only showed significant differences in test 4, and here there were 80% more errors in D than in A (significant at 1% level in a t-test).

Discussion.

In test 9 an improvement was shown when the subjects were exposed to noise C. However, this seems very unlikely, and as test 9 is similar to test 2 where no significant changes were seen, the significance was probably random.

Except for the above mentioned, all alterations in performance appeared as deteriorations when the subjects were exposed to noise D. This seems to indicate that infrasound above the threshold value is able to affect task performance in a negative way.

It is remarkable that no significant changes were seen when the subjects were exposed to traffic noise (B). This indicates that the recorded parameters are not very susceptible to noise. Traffic noise at L_{eq} = 71 dB is subjectively rather disturbing, and the results seem to show that the human being - at least for a few hours - is able to compensate for this, so tasks are carried out without deterioration. Thus task performance measurement may be a poor tool in noise assessment.

With this in mind, the significant deteriorations in performance caused by audible infrasound may be regarded as being more serious than their magnitude immediately seems to indicate.

In the present design of the experiment (latin square) the learning effect is balanced out, but it still contributes to the standard deviation. A further study of this effect might lead to a compensation giving smaller standard deviations and thus more significant changes in performance.

Acknowledgements.

The author wishes to acknowledge the important assistance of M. Sc. Gunnar Langkilde, B. Sc. Bjarne Kirk and B. Sc. Anders B. Mortensen.

References.

1. C. STANLEY HARRIS, DANIEL L. JOHNSON: Effects of infrasound on cognitive performance. *Aviation, Space and Environmental Medicine, vol.49, no. 4, 582-586, 1978.*

2. PHILIP M. EDGE, WILLIAM H. MAYES: Description of Langley low-frequency noise facility and study of human response to noise frequencies below 50 cps. *NASA Technical Note D-3204, National Aeronautics and Space Administration, Washington D.C., January 1966.*

3. BOB R. ALFORD, JOHN BILLINGHAM, A.C. COATS, B.O. FRENCH, JAMES F. JERGER, R.O. McBRAYER: Human tolerance to low frequency sound. *Transactions of American Academy of Ophthalmology and Otolaryngology, vol. 70, 40-47, 1966.*

4. R.A. HOOD, K. KYRIAKIDES, H.G. LEVENTHALL: Some subjective effects of noise. *British Acoustical Society Meeting on Infrasound, 26th November 1971, University of Salford, 1971.*

5. H.G. LEVENTHALL: Man-made infrasound - its occurrence and some subjective effects. *Colloque International sur les Infra-sons, 24-27 Septembre 1973, Paris. Proceedings edited by L. Pimonow, 129-152, 1973.*

6. K. KYRIAKIDES, H.G. LEVENTHALL: Some effects of infrasound on task performance. *Journal of Sound and Vibration, vol. 50, no.3, 369-388, 1977.*

7. J. MARGARET EVANS, W. TEMPEST: Some effects of infrasonic noise in transportation. *Journal of Sound and Vibration, vol. 22, no.1, 19-24, 1972.*

8. PAUL BORREDON, JEAN NATHIE: Effets physiologiques observes chez l'homme expose a des niveaux infrasonores de 130 dB. *Colloque International sur les Infrasons, 24-27 Septembre, Paris. Proceedings edited by L.Pimonov, 61-84, 1973.*

9. PAUL BORREDON, A. GIBERT, JEAN NATHIE: Etude chez l'homme des effets physiologiques d'une exposition a des niveaux infrasonores de 130 dB. *AGARD conference no. 145 "Vibration and combined stresses in advanced systems", Oslo 22.-23. april 1974. (Editor: H.E. von Gierke).*

10. R.J. ALFREDSON, N. BRONER, T.J. TRIGGS: Low frequency noise and testing for its effects. *Vibration and Noise Control Engineering Conference, Sydney 11-12 October 1976. The Institution of Engineers, Australia. National Conference Publication no. 76/9.*

11. HENRIK MØLLER: Construction of an infrasound test chamber (in danish). *R-77-8, Institute of Electronic Systems, Aalborg University Centre, November 1977.*

12. HENRIK MØLLER: Infrasound project at Aalborg University Centre. *Institute of Acoustics Meeting on Low Frequency Noise, 5th January 1979, Chelsea College, London.*

13. GUNNAR LANGKILDE: The influence of the thermal environment on office work. *In P.O.Fanger and O.Valbjørn (Eds.): Indoor Climate, Danish Building Research Institute, Copenhagen 1979, pp. 835-856.*

14. C.H. AMMONS: Tasks for study of perceptual learning and performance variables. *Percept. Mot. Skills, vol. 5, 11-14, 1975.*

Conference on
Low Frequency Noise and Hearing

7–9 May 1980
at Aalborg University Centre
Aalborg, Denmark
Proceedings edited by
Henrik Møller and Per Rubak

Hearing of Low Frequency Sound and Influence on Human Body

Shinji YAMADA, Toshifumi KOSAKA,
Koichi BUNYA and Toshihiko AMEMIYA
Yamanashi University, Takeda 4 Kofu, 400 JAPAN

Summary:

Thresholds of audibility of low frequency sounds, aural maskings of them by white noises and annoyances resulting from them were measured. The influence on mice by a low frequency sound was measured. The regulatory standard of low frequency sounds was investigated.

(1) Introduction:

In Japan the problems of low frequency sounds occur at 60-90 dB. One of them causes feelings of pressure on the sufferers' chests, buzzing in their ears or seasickness etc. Another causes windows and/or doors to rattle because of low frequency sounds without winds, and the sufferers have vague fears. These phenomenons occur below bridges of highways, at exits of tunnels of Shin-kansen and near boilers etc.

(2) Experimental apparatus:

As shown in photo.1, a 50 cm diameter loudspeaker was moved sinusoidally by an oscillator and a 70W direct current audio power amplifier. For preventing the transmission of vibrations, a small box was positioned below the loudspeaker and pressure waves were transmitted through a vinyl pipe to a low frequency chamber. Subjects were seated in the chamber. A low frequency microphone (1-100 Hz) was set near the subjects. A small loudspeaker was positioned in the upper part of the chamber as a masker.

(2.1) Frequency analysis of low frequency sounds in the low frequency chamber:

The low frequency sounds in the chamber were analyzed with fast fourier transform. The differences between the levels of fundamental low frequency sounds and the levels of harmonics were 30-40 dB and the influence by harmonics of the loudspeaker could be neglected.

(2.2) Vertical vibration levels in low frequency chamber:

Vertical vibration levels on a seat and on the floor in the chamber were 40-55 dB and below the threshold of vertical vibration sensation. So the influence by vibration could be neglected.

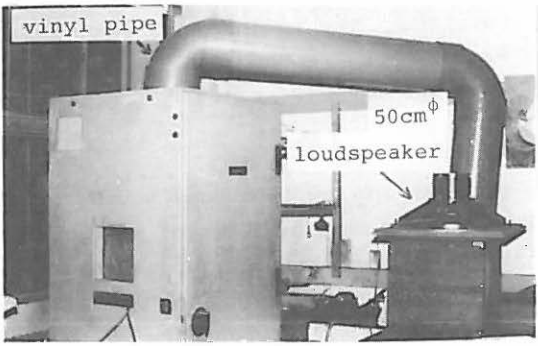


Photo.1 Low frequency chamber

(3) Measurement of threshold of low frequency sounds:

(3.1) Method of measurement:

Subjects were seated in the chamber and levels were slowly increased by a volume. When the subjects noticed low frequency sounds, they signed. For avoiding the influence of winds and other background noises, measurements were mainly done at night through a 1/3 octave band filter. In one frequency sound the same measurements were done three times. Each time their differences of levels were very small (1-2 dB). The subjects detected the existences of low frequency sounds by misty feelings of pressure in the ears.

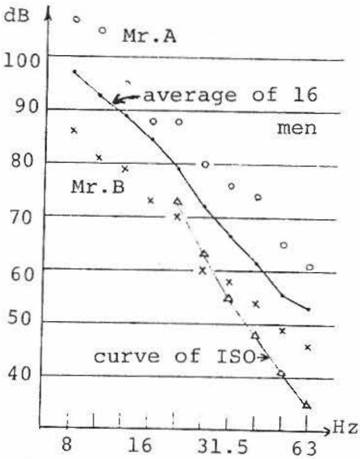


Fig.1 Threshold of hearing of men

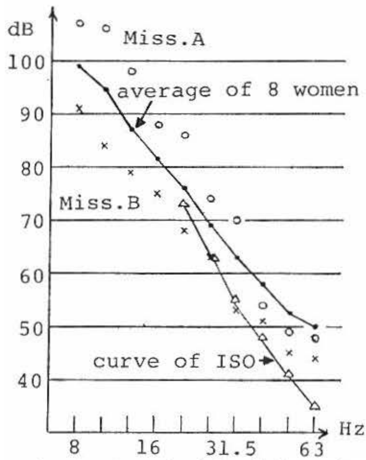


Fig.2 Threshold of hearing of women

(3.2) Thresholds of men:

The thresholds of men, who were university students and about 20 years old, are shown in fig.1. The difference between many persons is large and a very sensitive person has a lower threshold by 15 dB.

(3.3) Thresholds of women:

Thresholds of women, who were about 20 years old, is shown in fig.2. Women were 3 dB more sensitive than men, except for 8 and 10 Hz.

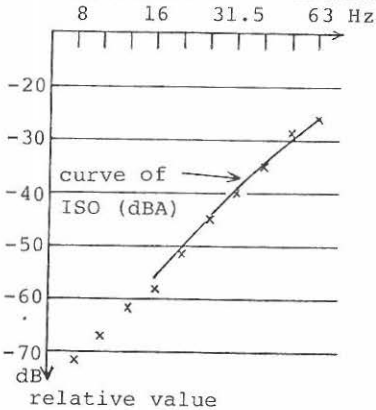
(3.4) Difference of ages:

The subjects, who were under 30 years of age, were 2-6 dB more sensitive than the others, who were over that age.

(3.5) A weighting curve and thresholds:

The average threshold at 63 Hz was 52 dB. For corresponding the auditory sensation weighting of ISO dB(A) (-26.2 dB at 63 Hz), 25.8 dB was subtracted from the average thresholds. As shown in fig.3, the auditory sensation weighting of dB(A) resembles to the threshold curve a little. To convert levels to dB(A) below 16 Hz, the values in fig.3 is used in this paper.

Fig.3 Curve of ISO(dBA) and that of threshold of hearing



(4) Aural masking by white noises:

White noises of 40 dB(A) were used as maskers. The increaces of the thresholds are shown in fig.4. Many subjects detected 30-40 dB(A) low frequency sounds (below 30 Hz) and there was about 10 dB increace of low frequency sounds thresholds. But one person (Mr.M) could distinguish low frequency sounds from white noises and his threshold did not increase. Sometimes it is said that infrasounds can be heard by the existence of harmonics that occur in the esrs and therefore they can be easily masked. But some persons can hear the infrasounds themselves. In Japan housewives, who live always in quiet rooms, are sometimes easily afflicted by low frequency sounds. This phenomenon happens, because there are no noises as maskers in quiet rooms and they can hear low frequency sounds easily.

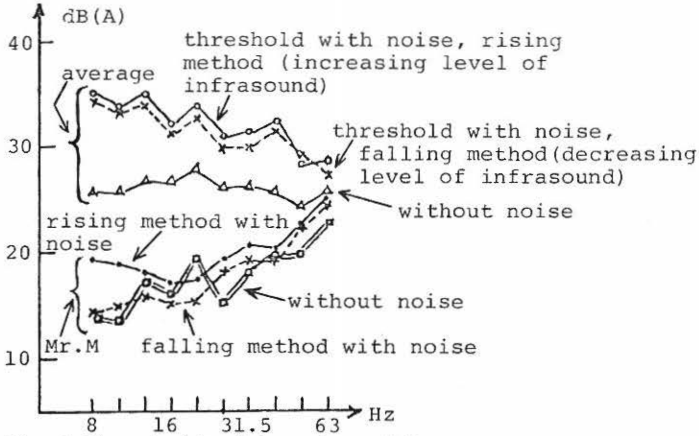


Fig.4 Threshold of hearing with 40 dB(A) white noise masker

(5) Influence on human body by low frequency sounds:

Subjects, who were mainly about 20 years old and seated in the chamber, were exposed to low frequency sounds for three minutes. Subjects were permitted to read their favorite journals in the chamber. When they did not feel ill at all, the levels were increased and they were exposed to low frequency sounds once more. When they felt ill or disagreeable a little, that was the threshold of annoyance. Subjects were exposed only for three minutes. If they are exposed for a longer time, they will surely feel ill in that levels of the thresholds of annoyance. The results are shown in fig.5. This shows that low frequency sounds below 16 Hz over 100 dB cause annoyance to human body. Difference between the thresholds of hearing and the thresholds of annoyance are shown in fig.6. This shows that in very low frequency sounds the difference between two thresholds is very small. And if somene hears very low frequency sounds in his/her house for long time, he/she will feel ill. At 8 Hz there is a very low point in fig.6. That is the man, who is annoyed by low frequency sounds. The symptoms were as follows: "feel disagreeable", "have headaches", "be languid in the body", "feel pain in the heart", "feel pain between the neck and shoulder", "heart beats increase", "get seasick", etc.

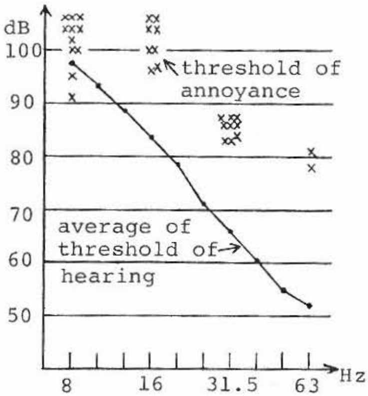


Fig.5 Threshold of annoyance

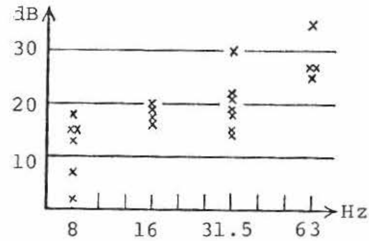


Fig.6 Difference between threshold of hearing and that of annoyance

(6) Influence on mice by low frequency sounds:

Audible frequency range of a mouse was measured by using conditioned reflex. It was over 1000 Hz. But in Japan low frequency problems occur at near 16 Hz, and so experiments were done at 16 Hz. A groupe A of 8 mice was exposed to 16 Hz 120 dB sound and another groupe B of 7 mice was exposed to 16 Hz 80 dB sound for ten hours/a day. Experiments were continued for 100 days (from 5th April to 13th July). There were no differences between the two groupes in the increace of the weight of their bodies and the weight of the water and food, eaten by each groupe. After the experiments, three mice were anatomized. But there were neither ulcers nor any other symptoms. As the sound of 16 Hz is very far from audible frequency range of mice, there was no influence on mice at all.

(7) Excitation of rattling noises by low frequency sounds:

When windows and doors are exposed to low frequency sounds over 70 dB, sometimes rattling noises are emitted as shown in fig.7. The sound of 16 Hz 70-80 dB is below the threshold of hearing and in spite of no existence of an audible sound and wind, windows or doors rattle. That phenomenon makes inhabitants feel anxiety. I think that the regulation should be below the threshold of rattling noises.

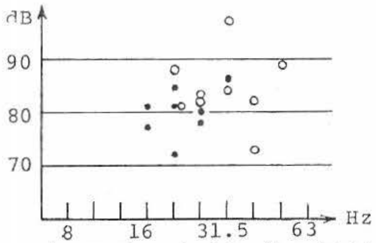


Fig.7 Threshold of rattling noises of windows (• wood frames o iron frames)

(8) Conclusion:

In Japan low frequency sounds make windows and doors (especially in wooden houses) vibrate and emit rattling sounds. And some people (especially housewives), who are sensitive to low frequency sounds and always live in the same quiet houses, hear the low frequency sounds and are annoyed by them. If this condition continues, sufferers suffer from stress and nervous diseases. For avoiding the occurrence to victims, the regulation should be below the threshold of hearing, the threshold of annoyance and that of rattling noises.

In factories or in cars noise levels of audio frequency range are large and so there are not so many problems by low frequency sounds. But sometimes the levels of low frequency sounds are very large and it may vibrate semicircular canals and cause physiological influences on human bodies. Other regulations may be necessary.

References:

[1] N.Broner, The effects of low frequency noise on people-A review, Journal of Sound and Vibration, (1978) 58(4), 483-500.

[2] W.Tempest et al, Infrasound and low frequency vibration, Academic Press (1976).

Acknowledgements:

We would like to thank Mr.Ohara, Asaoka, Tsuchiya, Hasegawa and Hanamoto for their helps.

Supplement of

"Hearing of Low Frequency Sound and Influence on Human Body"

Shinji YAMADA, Toshifumi KOSAKA,
Koichi BUNYA and Toshihiko AMEMIYA
Yamanashi University, Takeda 4 Kofu, 400 JAPAN

(Proceedings of the Conference on Low Frequency Noise and Hearing)

(1) Mean and minimum values of thresholds of hearing:

Minimum values of thresholds were selected at each frequency. The minimum and mean values of thresholds are shown in fig.1. The minimum values are lower than the mean values by 10-15 dB.

(2) Low frequency noise levels in sufferers' houses:

The frequency distributions of low frequency noises in sufferers' houses are shown in fig.1 and the frequency distributions measured by doctor Shiomi [lit.1] are shown in fig.2. Noise levels are positioned between the mean values and the minimum values. This shows that low frequency noise problems occur when sensitive persons hear (or feel in the ears) low frequency noises continuously, of which levels are nearly equal to their thresholds.

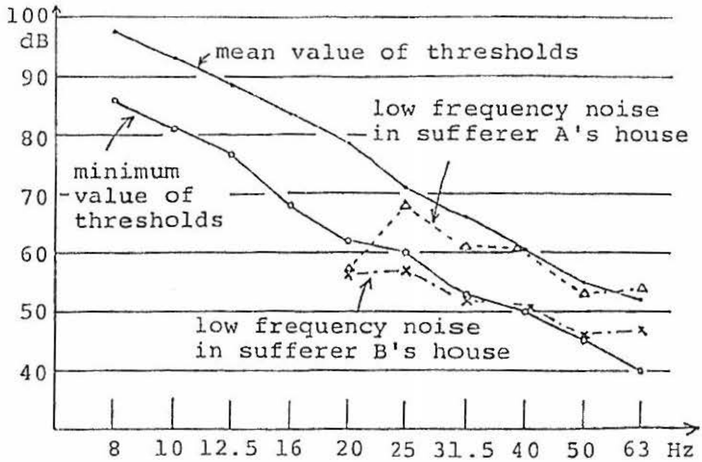


Fig.1 Mean values and minimum values of thresholds of hearing, and low frequency noises in sufferers' houses.
Low frequency noise source
to A's house is a cyclone separator,
to B's house may be the boiler of a neighboring house.

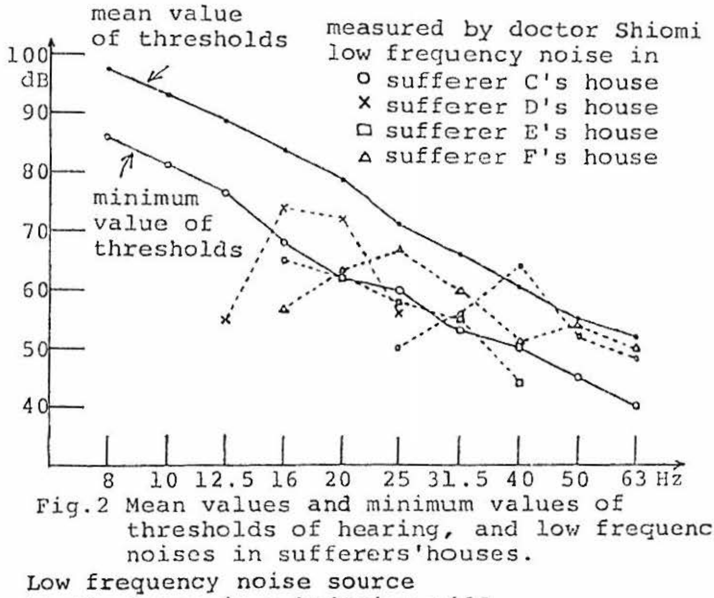


Fig.2 Mean values and minimum values of thresholds of hearing, and low frequency noises in sufferers'houses.

Low frequency noise source
to C's house is a knitting mill,
to D's house is a knitting mill,
to E's house is a mill of cotton-seed oil,
to F's house is a refrigerator in a supermarket.

(3) Phenomenon of aftersensation:

Sufferer A is suffered by low frequency noises, which are shown in fig.1. When she heard the sound of 25 Hz in our laboratory, the phenomenon of aftersensation occurred. After the sound of 25 Hz was stopped, she heard (felt) the sound. This phenomenon may occur often in sufferers who are suffered by low frequency noises.

(4) Sensation of distance from a low frequency noise source:

The position of an audible normal frequency sound source can be identified and there is the sensation of distance from it. But in the case of a low frequency noise source there is no sensation of distance from it and there is some feeling that a whole body is envelopped by it. So sometimes sufferers have feelings that they are vibrated by low frequency noises.

(5) Mechanism of occurrence of low frequency noise problems:

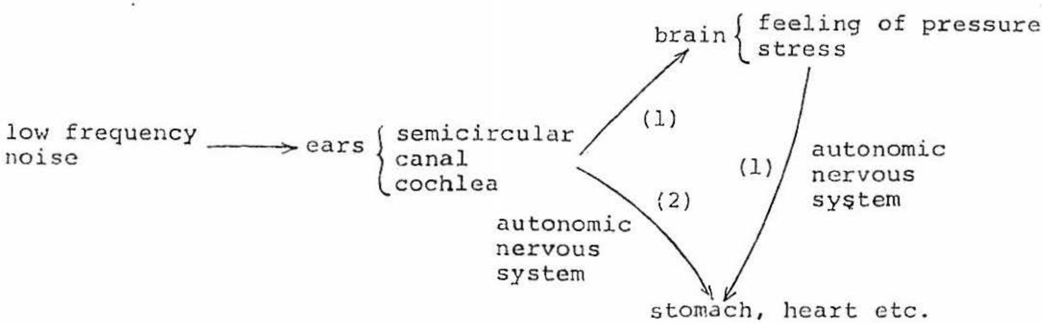


Fig.3 Mechnism of occurrence of low frequency noise problems.

Sufferers often consult physicians or neuropathists. Low frequency noises cause many symptoms of autonomic nervous systems in a heart or stomach etc. These symptoms happen, when a sufferer hears a low frequency noises and a brain is stimulated and some stresses are caused and the stresses cause some influences to autonomic nervous systems (the route (1) in fig.3). It may be supposed that the effect of the route (2) is not great except for the noises of special large levels. This mechanism resembles to that of vibration problems.

The development of some low frequency noise problems were as follows.

(1) One person was annoyed by noisy noises.
(Normal frequency noise + Low frequency noise)
(2) He/she became gradually sensitive and nervous to noises.
(3) As the regulation and a countermove were done by dB(A), the normal frequency noise was diminished and the low frequency noise remained.
(4) He/she, who was reduced to be sensitive and nervous, heard the low frequency noise and was suffered by it.

Normally a low frequency noise is masked by the existence of a normal frequency noise. But when this masker is removed and only the low frequency noise remains, a low frequency noise problem occurs.

Sufferers hear radios or televisions and open the windows of their houses all day long. This shows that sufferers want unconsciously to mask the low frequency noises by another sounds.

Recently in the usual life one of the authors (YAMADA) identifies the existence of low frequency noises of about 30 Hz from trucks or cars etc.. When he hears low frequency noises, he feels disagreeable "the ears are pressed by low frequency noises, the chest and head are vibrated by them, and when the level is high, the body vibrates." This is the halfway to become a sufferer by learning the low frequency noise.

Judging from these investigations, the regulatory standard of low frequency noises should be below the minimum values of thresholds of hearing to prevent the occurrence of low frequency noise problems perfectly.

Acknowledgement: We would like to thank Doctor F.SHIOMI.

[Lit.1] F.SHIOMI, Consideration of the damage of inhabitants caused by infrasound, Kogai-to-Taisaku, vol.14 NO.2 P159-166 (in Japanese)

Conference on
Low Frequency Noise and Hearing

7–9 May 1980
at Aalborg University Centre
Aalborg, Denmark
Proceedings edited by
Henrik Møller and Per Rubak

SOME EFFECTS OF INFRASONIC NOISE ON MAN.

Ulf Landström
NATIONAL BOARD OF OCCUPATIONAL SAFETY AND HEALTH
Department of Occupational Health
Technical Unit
Box 6104
S-900 06 UMEÅ
SWEDEN

SUMMARY

Human reaction to infrasonic noise has been examined through laboratory experiments and measurements at a working place. The production of infrasound for laboratory investigation was achieved with a low frequency pressure chamber. An examination was also made on workers exposed to infrasonic noise from a ventilation system. Different kind of physiological reactions were noticed. Infrasound was found to cause an increase in production of HCl from the stomach and a reduction of the respiration rate. Exposition reduced the systolic pressure but caused an increase of the diastolic pressure. A slight reduction in production of cortisol and adrenaline was also found. In the psychological tests an estimation of the wakefulness was included. The tendency to fall asleep during infrasound exposition was clear. The symptoms of tiredness was confirmed through EEG registration.

INTRODUCTION

During the last decades many sources of infrasonic noise have been identified and it has also been shown that there are high levels of infrasound in a variety of environments (Leventhall and Kyriakides, 1976). The first systematic and controlled investigations on whole body exposures were carried out in the sixties by Mohr et al. (1965) and Gavreau et al. (1966). Since then a variety of effects of infrasound exposures on humans have been observed. Infrasound may induce stress reactions, balance and auditory sensations, annoyance and fatigue. The present paper is a description of some physiological and psychological reactions following whole body exposition to infrasonic noise.

EXPERIMENTAL PROCEDURE

In the present laboratory investigation production of infrasound has been achieved with a pressure chamber of the dimensions 2,0 m by 1,6 m by 1,2 m (Lidström et al., 1978). Adjusting the size of the neck at the wall enables the chamber to operate as a Helmholtz resonator (Figure 1). By this construction it was possible to tune the chamber within the range of 5 Hz to 30 Hz.

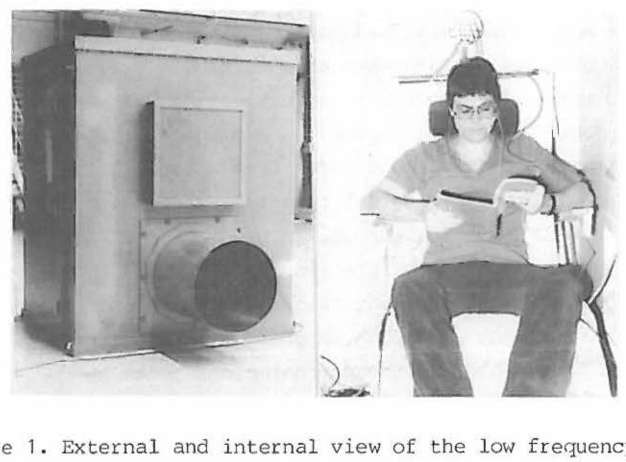


Figure 1. External and internal view of the low frequency chamber.

The sound was produced by eight, 50 W (diam. 10") loadspeakers which were driven by two 100 W power amplifiers. The maximum infrasound pressure level with closely controlled accoustic parameters fed into the chamber was 135 dB. The chamber was air conditioned and also provided with an intercommunication system and a window. The chamber accomodated a seated subject with an adequate margin of comfort (Figure 1). The experiments were carried out on healthy subjects of middle age. After being placed in the chamber the subjects were allowed to adapt for about 15 minutes. The investigation was then divided into three periods. One hour rest, followed by one hour exposition to infrasound (16 Hz) or a weak soughing noise (50 Hz) simulating the infrasonic sound. By this arrangement it was possible to make the subjects unconscious about the type of sound exposition. The investigation was ended with one hour rest.

RESULTS

By means of a gastric sound placed in the subject, collection of gastric juice was made at intervals of 15 minutes. The content of HCl was analysed by means of titrations. Figure 2 shows the effect of infrasonic noise on HCl production from the stomach.

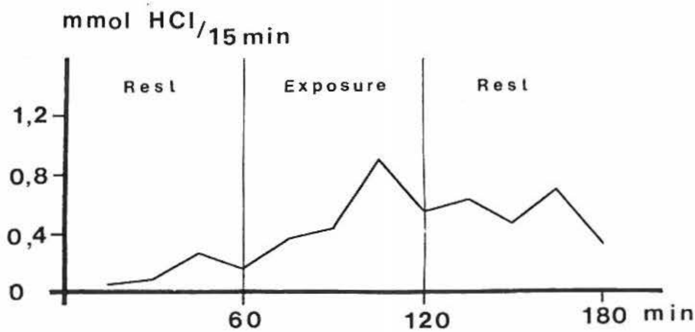


Figure 2. Changes in HCl production before, during and after exposition to infrasound (125 dB, 16 Hz) in one subject.

Of 20 subjects examined an increase in HCl production during exposition was found in 10. The top value during exposition varied between 0,43 and 2,99 mmol HCl/15 min. The avarage peak value was 1,24 mmol HCl/15 min (calculated on subjects affected by the exposition).

By placing a tension probe on the chest of the subject it was possible to registrate the rate of breathing. Exposition to the high frequency sound (HS) at 50 Hz did not cause any effect on breathing. Exposition to infrasound (IS) at 16 Hz and 125 dB however caused a reduction in rate of respiration (Figure 3). Of 14 subjects examined a reduction was found in 6.

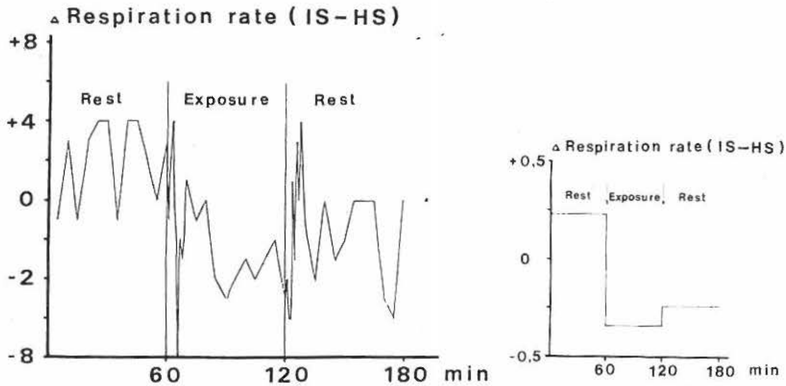


Figure 3. Left: Differences in number of pulmonary ventilations per minute in one subject before, during and after exposition to infrasound (calculated as the difference between breathing during IS and HS exposition). Breathing was registrated at intervals of 1–5 minutes. Exposition to HS or IS was made during the second hour. Value at rest = 15 ventilations per minute. Right: The same description showing an avarage curve calculated from measurements on 14 subjects.

No changes was found in EKG and puls activity. Infrasound however caused a reduction of the systolic blood pressure and an increase of the diastolic pressure (Figure 4). As seen from the figure, the effect is closely related to the period of exposure.

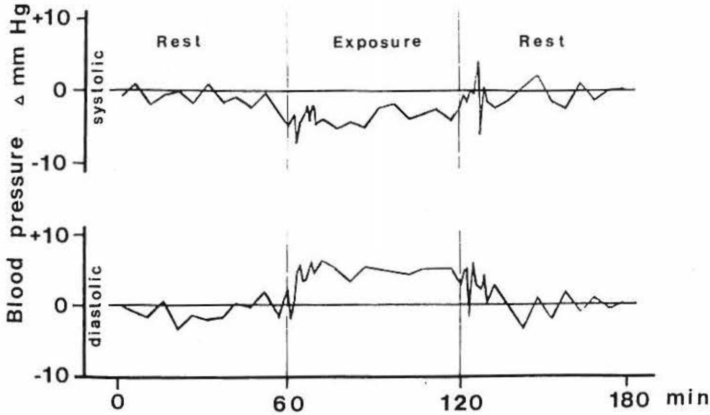
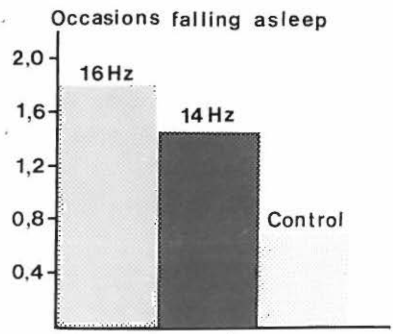


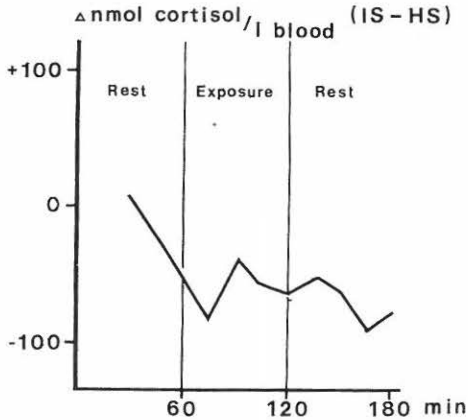
Fig 4, Variations in systolic/diastolic blood pressure, before, during and after infrasonic exposition (16 Hz, 125 dB). Pressure level before exposition standardized to 0 mm Hg. Number of subjects (n) = 20.

During the psychological tests it was possible to registrate changes in wakefulness. The tendency to fall asleep during infrasound exposition was clear (Figure 5). This effect was confirmed through EEG registration.

Figure 5. Number of occasions falling asleep (Average value per subject) during infrasonic exposition (16 Hz and 12 Hz, 125 dB). The control group was exposed to a weak soughing noise at 50 Hz. n=15 per group. Time of exposition = 2 hours.



An attempt was also made to examine the effect of infrasound on stress hormones. Through blood tests from subjects exposed in the chamber it was possible to registrate a slight reduction in production of cortisol (Figure 6).



Figur 6. Changes of cortisol in the blood, before, during and after exposition to infrasound (16 Hz, 125 dB). For further explanations see text to Figure 3. n = 12.

In a further test (Liszka et al. 1978) an investigation was made on personal subjected to infrasound at their working place (6-12 Hz, 70-90 dB). The test was made on 37 subjects daily exposed to infrasound from a ventilation system. Time of exposition was approximately eight hours per day. After the end of work there was a lower level of adranaline in their specimen of urine compared to the control group exposed to low infrasonic noise (Figure 7).

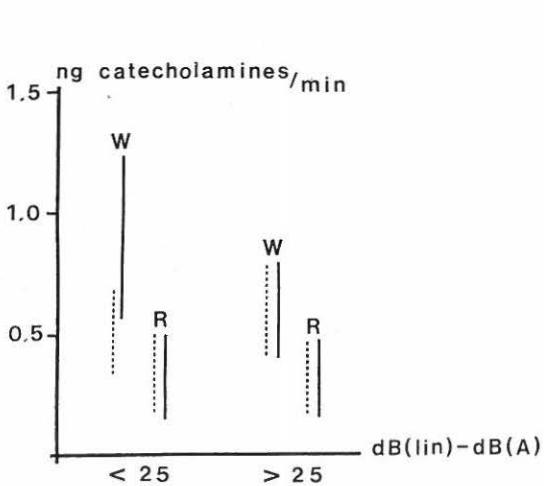


Figure 7. Changes in adrenaline/noradrenaline secretion during rest and work in two groups of workers (n=37). dB(lin)-dB(A) >25 = high infrasonic noise, dB(lin)-dB(A) <25 = low infrasonic noise. Dotted line = noradrenaline, continous line = adrenaline, W = end of work in afternoon, R = before work in the morning.

DISCUSSION

Although the work on physiological and psychological effects described here are still at a somewhat preliminary stage, the results of the tests in general confirm the hypothesis that infrasonic noise can produce different symptoms of weariness. Present observations about reductions in wakefulness, as shown by EEG recordings, are in good agreement with previous investigation by e.g. Fecci et al. (1971). The results obtained so far may also suggest that there is a connection between infrasonic exposure, reduced production of stress hormones and wakefulness. In what extent the observed changes in blood pressure and respiration rate are involved has not yet been investigated.

For lower levels of infrasound, annoyance has been suggested to be the main factor that dictates that exposure above audibility threshold should be avoided. Present investigation shows that these levels may also be correlated with changes in human physiological reactions, some of which are involved in alertness. The process by which infrasound affects the human reactions remains however obscure. There is a lot of literature (Guignard, 1968; Stephens, 1971; von Gierke, 1973; Leventhall and Kyriakides, 1974; Johnson, 1975) according to which infrasound can produce a mechanical stimulation in different parts of the body. There are some body resonances which can be stimulated by infrasound. Abdominal resonances have been observed at about 10 Hz and thorax resonances in the region of 20-70 Hz, depending on the stature and posture of the subject. It has also been shown that abdomen vibration may cause distress and sickness, whilst excessive chest vibration may interfere with the normal respiratory rhytm (Johnson, 1973, von Gierke and Nixon, 1976). Whether present observations about increase in HCl production and reduction in breathing rate can be explained by the resonance hypothesis is not clear yet. The situation is also complicated by the fact that some people are particularly sensitive to infrasound, more than others. The hypotheses clarifying the way by which infrasound exerts its effects upon human have yet little experimental support. It is hoped that further work will clarify the position.

REFERENCES

Fecci, R., Barthelemy, R., Bourgoin, J., Mathia, A., Eberle, H., Moutel, A and Jullien, G.: Effects of infrasound on the organism. La Medicina del Lavoro, 62, 130-150, 1971.

Gavreau, V., Condat, R and Saul, H: Infrasons: generateurs, detecteurs, propriétés physiques, effets biologiques. Acustica, 17, 1-10, 1966.

Guignard, J.C.: Human response to intense low frequency noise and vibration. Proceednings of the Institution of Mechanical Engineers, London, 182, 67-71, 1967-68.

Johnson, D.L.: Auditory and physiological effects of infrasound. Inter-Noise 75, Sendai, 475-482, 1975.

Johnson, D.L.: Effects of Infrasound on Respiration. Presented at the 44th Meeting of the Aerospace Medical Association, Las Vegas, Nevada, May, 1973.

Leventhall, H.G. and Kyriakides, K.: Acoustically induced vibrations of the body. Presented at the Annual Conference of the U.K. Group on Human Response to Vibration, Yeovil, September, 1974.

Leventhall, H.G. and Kyriakides, K.: Environmental Infrasound: its Occurence and Measurement. In: Infrasound and Low Frequency Vibration. Editor: W. Tempest. Academic Press. London, 1976.

Lidström, I.-M., Liszka, L., Englund, K., Hagelthorn, G., Lindqwist, M., Söderberg, L. and Hörnqwist, S.: Infraljudets effekter på människan. (In Swedish). Undersökningsrapport 1978:33. Arbetarskyddsstyrelsen, 1978.

Liszka, L., Danielsson, Å., Söderberg, L., Lindmark, A.: En undersökning av långtidseffekter av ventilationsbuller på människor. (In Swedish). Undersökningsrapport 1978:34. Arbetarskyddsstyrelsen, 1978.

Mohr, G.C., Cole, J.N., Guild, E. and von Gierke, H.E.: Effects of Low Frequency and Infrasonic Noises on Man. Aerospace Med., 36, 817-824, 1965.

Stephens, R.W.B.: Very low frequency vibrations and their mechanical and biological effects. 7th International Congress on Acoustics, Budapest, 1971.

von Gierke, H.E.: Effects of infrasound on man. Proceedings of the Colloquium on Infrasound. Centre National de la Récherche Scientifique, Paris, Septembre, 419-435, 1973.

von Gierke, H.E. and Nixon, C.W.: Effects of Intense Infrasound on Man. In: Infrasound and Low Frequency Vibration. Editor: W.Tempest. Academic Press. London, 1976.

Conference on
Low Frequency Noise
and Hearing

7–9 May 1980
at Aalborg University Centre
Aalborg, Denmark
Proceedings edited by
Henrik Møller and Per Rubak

ANNOYANCE CAUSED BY LOW FREQUENCY/LOW LEVEL NOISE

H. G. LEVENTHALL, CHELSEA COLLEGE, UNIVERSITY OF LONDON,
PULTON PLACE, LONDON, SW6 5PR.

Summary

Factors involved in annoyance are discussed and illustrated with field experience which shows the limitations of existing criteria when applied to low frequency/low level noise.

Noise criteria are often considered to be deficient when dealing with low level noise, the effect of which depends on a number of complicated factors. The criteria are particularly deficient when the noise is of low frequency as well as low level. Significant changes at the low frequency end of the spectrum might be clearly perceptible but have a negligible effect on, for example, the dBA level. It is possible to reduce the dBA level whilst increasing the loudness sensation, and there is an indication that this may be happening in some noise control work where machinery manufacturers are shifting the noise energy out of the range which is significant for dBA, but making the noise subjectively louder. In general, low level/low frequency noises become annoying when the masking effect of higher frequencies is absent. This can occur, for example, in transmission through walls and propagation over long distances, since in both these cases, higher frequencies are attenuated more rapidly. An important factor in relation to annoyance is the rate of fall of the spectrum in the middle and higher audio frequencies. The more rapid the fall-off, the more annoying is the noise.

The assessment of subjective response to a low frequency noise is complicated by the individual differences which exist, particularly in the region of threshold. A situation may arise in which only one person in a household is affected by a noise and this results in additional stresses produced by their isolation. The low frequency threshold is shown in Fig. 1. There are differences between the lower end of the ISO threshold and threshold data obtained in low frequency chambers. One point which became clear in threshold measurements was that there is a more sharply defined onset of sensation at the lower frequencies. This is in accordance with variation in equal loudness contours which are known to be much closer together at the lower frequencies. For example, the whole range from threshold to feeling is covered by about 130 dB at 1000 Hz but by only about 70 dB at 20 Hz. It is usually stated that an increase in level of 10 dB gives a doubling of loudness sensation. Whilst this is correct at higher frequencies, the figure is nearer 5 dB per doubling of loudness at the lower frequencies and lower levels. The overall effect is that there is a more rapid growth in loudness sensation with increase of level through threshold at the lower frequencies than there is at higher frequencies. Another factor which may be relevant at the lower frequencies is that of microstructure in the threshold curve. It is known that in the region of 1000 to 1500 Hz the threshold may vary by as much as 15 dB over a range of about 20 Hz. If it is shown that the lower frequency region, i.e. 10 to 100 Hz, is subject to similar fluctuations, an explanation of some of the wide differences in individual response could follow. So far we have only looked for the low frequency microstructure in a few subjects and were unable to find it.

One effect in the low frequency region is that of "tuning in". Here the annoyance of the noise increases with time, sometimes apparently associated with an increased loudness effect. Accommodation to noise, which often occurs at higher frequencies, appears to be more difficult at the lower end. The subject becomes increasingly sensitive to the noise and, after a protracted period, may develop physical symptoms which cannot be explained in terms of direct action of the noise on the body. The symptoms are typical of those produced by stress, e.g. headaches, pains in the neck, arms and legs, digestive disorders. The symptoms can be produced by noises at very moderate dBA levels.

A further effect is related to whether or not the noise source is identifiable. If it is identifiable, there is a focus for the complaint about the noise, but it is not always possible to achieve a satisfactory outcome. For example, the Environmental Health Officer might be called in, but on the basis of the dBA reading which he would normally take, he may feel that noise criteria are not exceeded. Further, if he himself cannot hear the noise, he could find it difficult to press matters on behalf of the complainant. An unidentifiable source presents particular difficulties which are magnified if only a few people hear the noise. What can you do about a noise if you do not know where it comes from? This is a situation with many examples of environmental low frequency noise complaints. A further complicating factor is the possibility of low frequency tinnitus. Our own work has convinced us that some low frequency noise complainants do suffer from tinnitus, just as we are equally convinced that some do not. One should not take the easy way out and dismiss all complainants as tinnitus sufferers, although this may be more likely when only one person hears a noise from an unidentifiable source. There may be the possibility of a combination of a spectrum peak in the noise with a sensitivity peak in the threshold, assuming these occur.

A substantial number of people are disturbed by low frequency noise. We have carried out surveys of complainants who were asked to complete an hourly questionnaire rating their subjective appreciation of the noise on a five point scale from absent through 'Quiet', 'Mild', 'Heavy', 'Very Heavy' and 'Violent' (these are the descriptions chosen by the subjects). Fig. 2 shows a typical month's response in which the average responses of about 30 people are shown throughout the day for different days in the month. The overall picture is of increased annoyance in the early hours of the morning and late at night. The average responses by time of day over a three month period indicated that in the early hours of the morning, the people who were disturbed by a low frequency noise, classified it, on average, as 'Heavy'. The noise eased around mid-day but worsened as the evening progressed. These people were not only annoyed, some of them were very badly upset, even to the point of becoming suicidal. The fact that they filled in survey forms for each hour of the day over a long period is an indication of their motivation and of the effect which the noise was having on them.

Some examples of annoying low frequency/low level noises are as follows: Fig. 3 shows two examples of noise in living accommodation produced by machinery in adjacent premises. Both occurred in Central London and were causes of persistent complaints leading to threats of legal action. The levels are low, but a one third octave analysis of this type, which averages the signal, does not reveal the true nature of the noises. They both had an unpleasant throbbing characteristic of about one per second and it was this which made the noises particularly noticeable and unpleasant rather than their average levels. They may have been tolerable if they had not been fluctuating. Fig. 4 gives the noise from a boilerhouse. Again average levels are shown, and although these are beneath the normal threshold there were fluctuations which could have caused thresholds to be exceeded and result in complaints from a sensitive person. There are no criteria which could have judged this noise to be excessive, but persistent complaints resulted in an abatement order. However, the complainant moved house before work could be carried out. Fig. 5 is an example of lift noise in a block of apartments. The location was particularly quiet at night and the noise is more than 10 dB above background. The complaint was of sleep disturbance at night. Assessment of the noise in terms of, for example, Leq, gives only a small increase above background because of the few lift movements involved. However, if a complainant is woken up several times an hour throughout the night, it is of no help to tell him that the equivalent level is still quite low. Clearly a sleep disturbance criterion is required. The tenant took legal action against the owners of the apartments, but the case was settled out of Court with several thousand pounds compensation and a move to another flat.

Fig. 6 illustrates an environmental noise from an unknown source. The complainant was able to distinguish the level changes although the experimenter could not hear either noise. This analysis is also an average so that fluctuations could be somewhat greater than the levels shown. Fig. 7 shows noise measured on two different occasions at a location in the New Forest. There is variation within a fairly short period of time on each occasion. In one case there is an increase overall of about 10 dB after a half hour interval whilst, on the second occasion, there is a decrease of about 20 dB over a similar interval.

These instances of annoying low frequency/low level noise indicate the need for expansion of existing criteria. Are we to have criteria which cover the more sensitive people as well as those of average sensitivity? How are we to assess a throbbing characteristic of a noise and how are we to account for sleep disturbance, individual threshold differences and low frequency tinnitus?

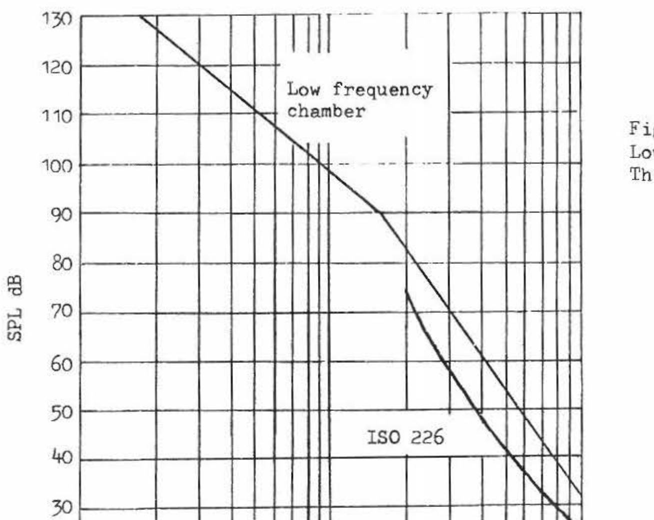


Fig. 1
Low Frequency
Thresholds

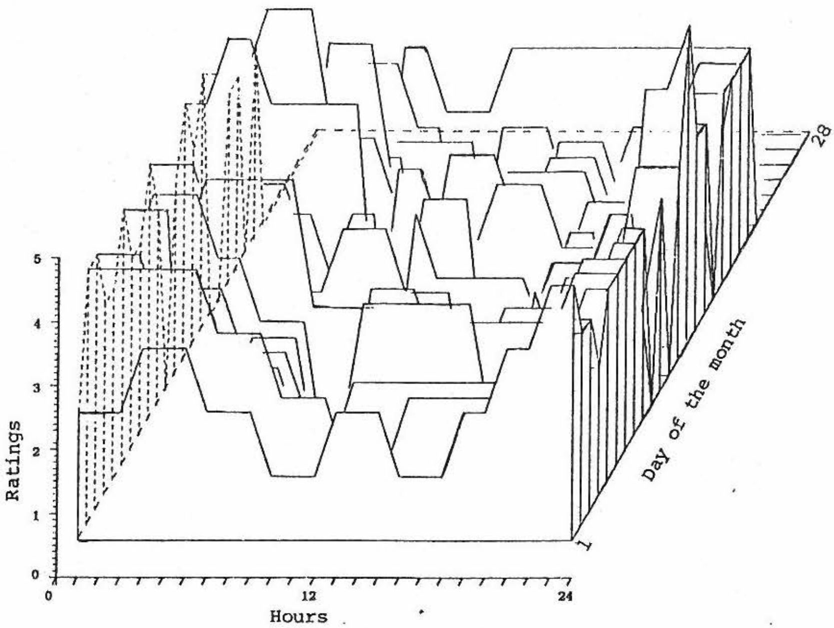


Fig. 2 Diurnal variation during August, 1977

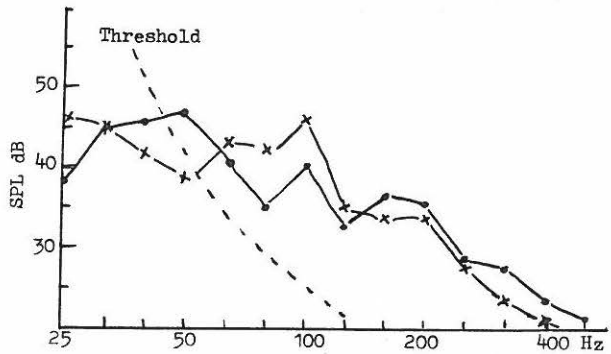


Fig. 3 Noise From Adjacent Presmises

—•—•— Dry cleaners 31 dBA

—×—×— Air conditioning plant 32 dBA

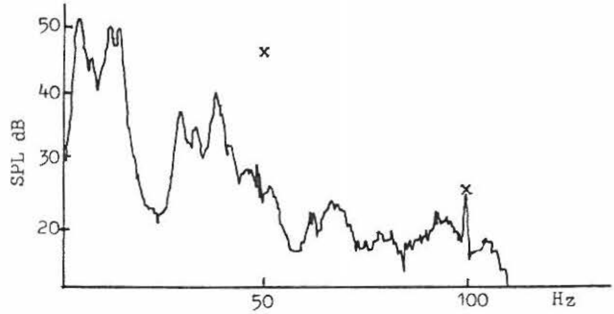


Fig. 4 Boiler House Noise in Adjacent Flat

x Threshold Levels

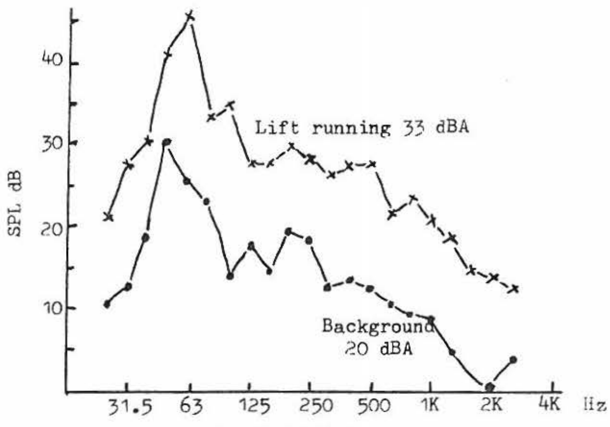


Fig. 5 Lift Noise

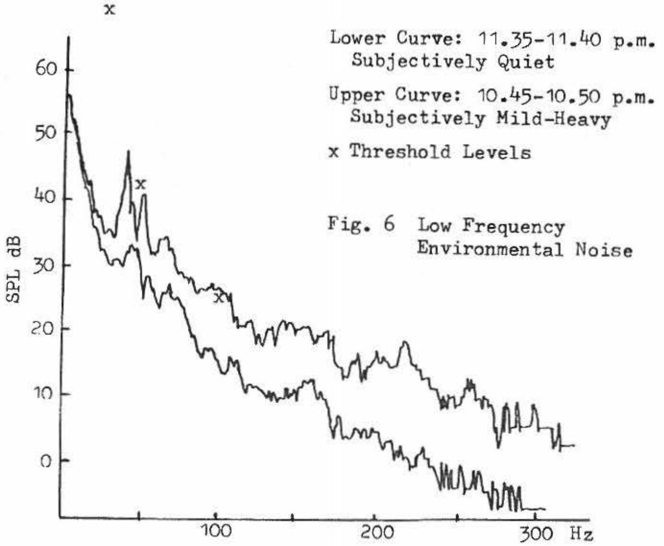


Fig. 6 Low Frequency Environmental Noise

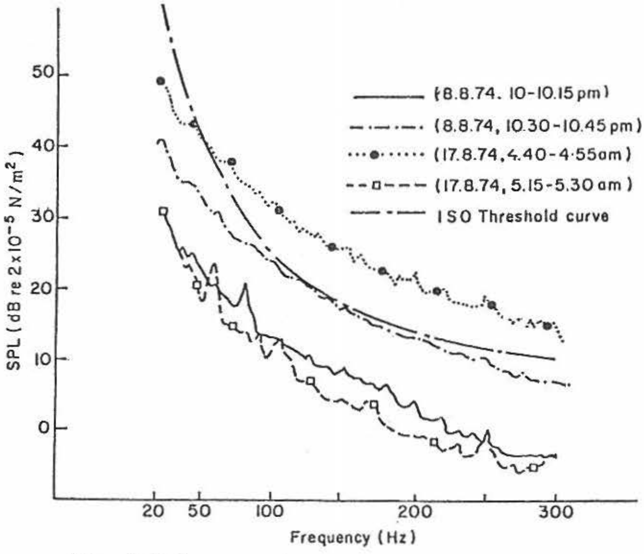


Fig. 7 Indoor spectra at a location in New Forest

Conference on
Low Frequency Noise and Hearing

7–9 May 1980
at Aalborg University Centre
Aalborg, Denmark
Proceedings edited by
Henrik Møller and Per Rubak

PHYSIOLOGICAL PARAMETERS IN HUMAN RESPONSE TO INFRASOUND

O. Okai (Dept. Physiol. Kyorin Univ. Sch. of Med., Shinkawa 6-20-2, Mitaka, Tokyo 181,), M. Saito, M. Taki, A. Mochizuki (Inst Med. Elec., Fac. Med, Univ. Tokyo) N. Nishiwaki, T, Mori, M. Fujio (Nishiwaki Labo.).

This paper deals with human physiological parameters, including threshold of sensation, in response to infrasound (IFS). The results yielded are as follows: 1) threshold of sensation for a sensitive subject to IFS is much lower than that for normal ones, 2) both heart and respiratory rates decreased during first one-minute IFS exposure, while the rates increased during one-hour 120 dB IFS exposure, 3) change in the respiratory rhythm for a sensitive subject to IFS took place during one-hour 120 dB exposure, 4) sphygmogram of pulmonary circulation indicated that amplitude of the wave increased with increasing IFS level, 5) blinking rate also increased during IFS exposure with increasing frequency, 6) alpha rhythm amplitude of EEG decreased during exposure of IFS intensity of juzta-threshold intensity, 7) Driving effect of IFS was most remarkable at 9 Hz. 8) Nystagmus was observed in a case of overworked subject during 20-minute 120dB IFS exposure, 9) nausea and vomiting was

Shown in a subject with a cold during latest phase of 10 minutes IFS exposure.

1. Introduction

Modern industrial machines sometimes generate a high level steady IFS. Probably, man has long been exposed to natural and artificial IFS. Recently, an attention is directed to various physiological effects on man which are attributable to artificial IFS. We have been conducting researches on this effects.

2. Methods

Experimental arrangement: For the measurement of human physiological parameters an experimental set-up consisting of relatively small room with excellecnt electrical and acoustic shieldings was prepared. In this room an examinee was comfortably sit or lay down. This is also equipped with an array of speakers of considerably large outputs and an electronic system for the monitoring of the parameters. The IFS field can be controlled up to some 100dB at the position of the examinee, while background noise is kept below 50 dB. Firstly, the threshold of sensation for the IFS was examined by a conventional threshold-detecting techniqe in the subject. Secondly, physiological responses were observed from outside of the shield room. The measurement are made, for example on heart rate, blood pressure, respiratory frequency, sphygmogram of pulmonal circulation, EEG and blinking.

Physiological parameters: Physiological parameters were detected by the maneuvers: 1) heart rate by sphygmograph following attached on a finger, 2) blood pressure by Riva-Rocci procedure, 3) respiratory frequency by impedance plethysmograph (electrodes were placed on the chest and the back of right side), 4) sphygmogram was measured by the same procedure as repiratory frequency with the breath-holding, 5) EEG electrodes were placed at the temporal and mastoidal regions, 6) blinking by an electrocardiograph (electrodes were placed at superior and inferior palpaeblae), 7) movement of the stomach was by a baloon, fieled with water, inserted in the stomach of a dog.

Exposure time, frequency and intensity of IFS: Exposure time was from one minute to one hour. The range of frequency covered was from 8 to 50 Hz. The sound pressure level was varied from 50 to 130 dB. The frequency wad selected among various frequencies which was most uncomfortable for a subject.

Subjects: The examiners were 20 to 60 years old, 28 male and 2 female, Two of them were sensitive to infrasound, one was overworked and another one had caught a cold.

3. Results and discussion

Threshold of sensation: For the measurement of the threshold (Fig. 1) of sensation the intensity of the IFS in the shielding room is raised from the value well over the threshold, until the subject recognized that he can feel the IFS, or the intensity is reduced from the value well below the thresold. Then, he pushes a switch to provide the record of his threshold for each frequency. In this case infrasound is acompained by higher masking frequencies such as white noise at 72 dB over all sound pressure [4,5].

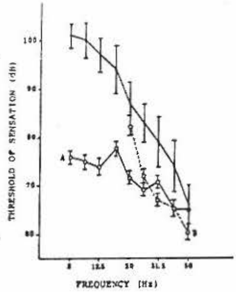


Fig. 1 Thresholds of sensation for various low frequencies.

The result 28 healthy subjects is shown by the solid line in Fig. 1. This resul was very reproducible and agree well with the result previously reported [1,2,6,7]. We noticed, however, a very interesting phenomen: Among subjects with the complaints of the environmental IFS, there are those people who seem to be more sensitive or too nervous to the IFS. Several of such subjects are invited to become exminee, with the results shown by dashed-line in Fig. 1. It should be noted that the results for these people were quite reproducible. Thus, undoubtedly these subjects can sense the IFS well below threshold for normal subjects (30dB at maximum). The difference between the sensitive and normal people is remarkable in some time at lower frequencies and in other time at higher frequencies.

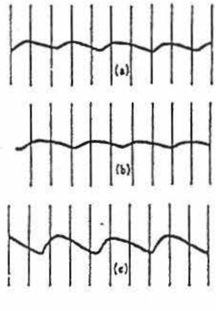


Fig. 2 Sphygmogram during 1-minute IFS exposure of 10(b) and 20 Hz(c) at 100 dB; (a) control.

Physiological effects

Heart rate: Various physiological examination were made exposure to relatively strong field of 10 and 20 Hz at 100 dB. Heart rate was calculated by shygmogram. Heart rate, for example, decreased during one-minute exposure (Fig. 2).
The results in 30 subjects are shown in Fig. 3. If the heart rate ratio (HRR) denotes the heart rate exposed to IFS divided by the control heart rate, HRR are less than unity. But thereafter, HRR increases during one-hour IFS exposure (Fig. 4): Heart rate may be accelerated of decelerated partly by the respiratory center because heart rate chages along with the respiratory rate under IFS exposure. (Fig. 6). Similar results were reported elsewhere [5].

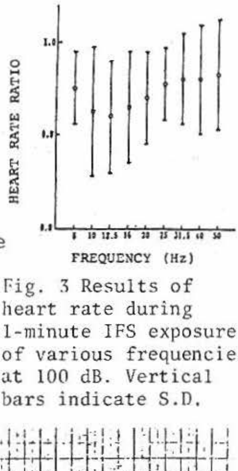


Fig. 3 Results of heart rate during 1-minute IFS exposure of various frequencies at 100 dB. Vertical bars indicate S.D.

Blood Pressure: Under one hour infrasound exposure of various frequencies at 120 dB no special trend of blood pressure was observed. Almost the same observation was reported [7].

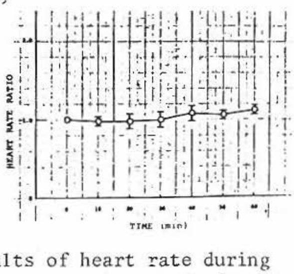


Fig. 4 Results of heart rate during 1-hour IFS exposure at 120 dB for 30 subjects. Vertical bars indicate S.D.

Respiratory rate and wave form: One of the conspicuous results was the effect on respiratory function. In most of the cases, especially at the onset of IFS exposure, there was a disturbances in the repiratory waveform followed by an increase in the rate of respiration, when IFS was stopped. An example of the respiratofy waveform is shown in Fig. 5; the arrows indicate the onset and the end of the IFS exposure. Fig. 6 shows the results of 28 healthy subjects. If respiratory rate ratio (RRR) denotes the respiratory rate under IFS exposure divided by control respiratory rate, the ratios are less than unity, i.e., RRR decreases under IFS exposure. But RRR increases during one-hour IFS exposure (Fig. 7). Almost the same studies were reported elsewhere[1,5,7]. Especially, one of the remarkable changes in respiration caused by one-hour IFS exposure at 120 dB, was the change in respiratory rhythm (Fig. 8). This may be caused by the effect of IFS on the lung, and/or by the vestibulo-respiratory reflex. Further studies about this should be required.

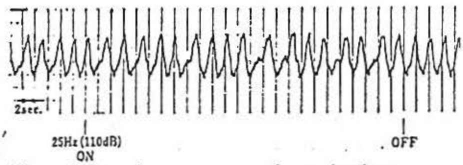


Fig. 5 Respiratory waveform during one-minute IFS exposure of 25 Hz at 110 db, Arrows indicate the start and end exposure.

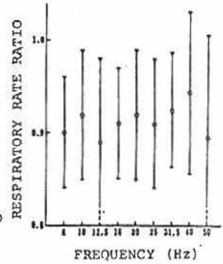


Fig. 6 Respitatory rate ratio during one-minute IFS exposure of various frequency at 110 dB. Vertical vars indicate S.D..

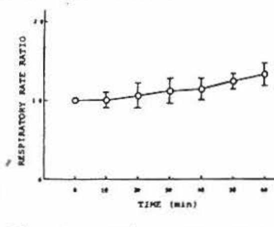


Fig. 7 Respiratory rate ratio during one-hour exposure at 120 dB. Vertical bars indicates S.D..

Sphygmogram of pulmonal circulation: IFS also affects pulmonary circulation (Fig. 9)

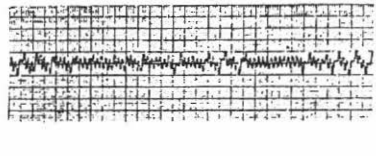


Fig. 8 Chanses in respiratory rhythm; Sphygmogram was superimposed on respiratory wave.

Heart rate decreased and the amplitude of the sphygmogram increases with increasing the intensity of IFS. An increase in the amplitude may be due to an increase in cardiac output and/or in compliance of the total pulmonary vascular bed.

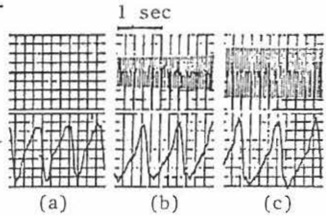


Fig. 9 Sphygmogram(bottom) of pulmonal circulation. In the top tracing the amplitude is propotional to IFS intensity; (a) control; (b) 65-70 dB; (c) 100dB

EEG: At the IFS intensity close to the sensation threshold the suppression of the amplitude of the EEG alpha wave is frequently observed (Fig. 10). Although it mechanism is still unknown, this effect may be utilized as an objecteve measure for determining the threshold of sensation. When the subject was exposed to stronger field over 100dB, with frequency close to that of the original alpha rhythm of the subject, synchronization of alpha rhythm to the driving frequency is often observed (Fig. 11): the same studies were reported elswhere[6].

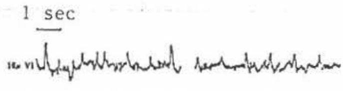


Fig. 10 Alpha wave(bottom) calculated from EEG(top) under IFS exposure at 60(left panel) and 96 dB(right panel).

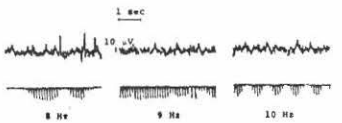


Fig. 11 Synchronization of alpha rythm(bottom) calculated from EEG(top).

Blinking: IFS changed from 8 to 50 Hz by a step of 1/3 octave at 120 dB was given to the subjects. Five-minute IFS exposure for various frequencies and five-minute interval were alternated. If blinking ratio denotes blinking rate for IFS exposure divided by blinking for the ante-

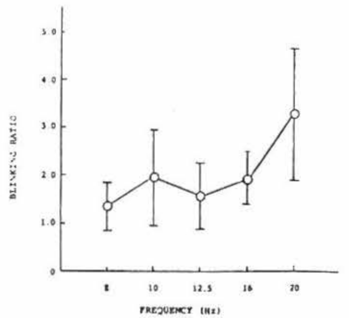


Fig. 12 Blinking ratios under IFS exposure of various frequencies at 120dB. Vertical bars show S.D..

cedent interval, the ratio increased with increasing frequency,(Fig. 12). An increase in blinking rate may be due to an increase in the velocity of the wind with increasing frequency.

<u>Movement of stomach</u>: Fig. 13 shows the pressure change in the stomach. A signal of 10Hz at 130 dB superimpose on ECG in upper tracing and pressure change caused by IFS appears in the lower tracing of the left panal. On ECG record(upper tracing of the right panel) signal of 20 Hz is superimposed. But no remarkable change appears in the lower tracing of the right panel. These evidences suggest that the stomach of a dog may be affected by 10 Hz IFS at 130 dB through the abdominal wall and this fact may possibly be true on human examinees.

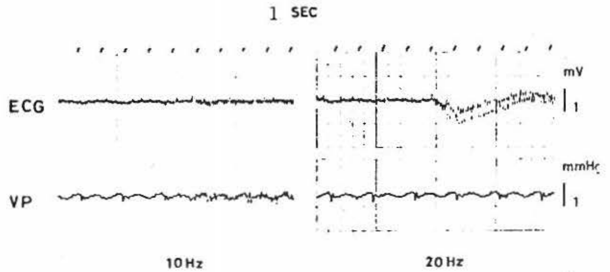


Fig. 13 Pressure shage under IFS exposure of 10 Hz(left (left) and 20 Hz (right) at 130 dB.

<u>Nystagmus</u>: A overworked subject was exposed to IFS of 20 Hz at 120 dB during one hour. After twenty minutes exposure nystagmus took place. The subject felt surounding structure shakenlike erthquake. As soon as the IFS was ceased, the nystagmus disappears (Fig. 14). Some reported the presence of nystagmus[6,7], others reported the absence of nystagmus [8]. Our consideration about this will be discussed later.

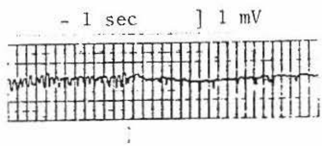


Fig. 14 Nystagmus under IFS exposure of 20 Hz at 130 dB Arrow shows the end of exposure.

<u>Nausea and vomiting</u>: A subject, with a cold, showed nausea and vomiting during ten minutes IFS exposure of 20 Hz at 120 dB. Fig. 15 shows the physiological signs where heart and

respiratory rates indicate irregular patterns. High frequency blinking is also observed. The same reports appeared elsewhere [7,9,10]. These signs may be attributable mainly to the disorder of the digestive system and to the vestiburo-intestinal reflex. The discussion about this will be discribed later.

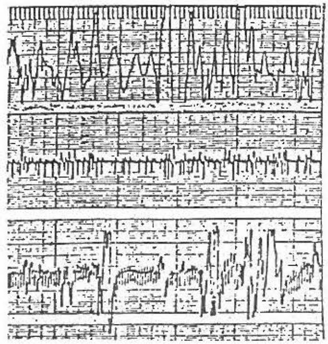


Fig. 15 Physiological respones when nausea and vomitting take place under IFS exposure of 20 Hz at 120 dB; Time marker shows 1 sec. (a) respiratory wave, (b)brinking (c) heart rate wave.

<u>Effect of IFS on human</u>: In general the effect of IFS on human may probably depend on intencity, frequency and exposure time of IFS, together with the conditions of the subject. If environmental and body factors denote the total effect of IFS and the effect on individual, respectrvely, effective environmental factor can be expressed as environmental factor minus body factor. Environmental factor is an integration of intensity and frequency of the IFS. Body factor also indicates a resistance against an illness. Consequently effective environmental factor may be measure the real effect of IFS on human. Furthermore, the effective environmental factor multiplied by time factor, which means exposure time of IFS, makes influence index indicates the total measure of the effect on human (Fig. 16).

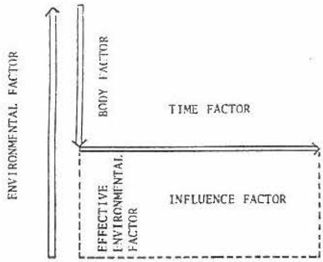


Fig. 16 Shematic representation of the effect of IFS in human.

The more people show a symtom, the influence index for the symptom may have theless value. When the measure is more than the threshold of, for example, mystagmus, the subject may show nystagmus. From this hypothesis nystagmus, nausea and vomiting are discussed here. We observed nystagmus of a subject exposed to IFS of 20 minutes at 120 dB. The same subject may need 17.1 minutes under the IFS at 140 dB from a simple calculation. In the study of Jonson[9] the exposure time may not be sufficient to produce nystagmus. As for nausea and vomiting the value of influence index is so great that few people show the symptom. When he falls ill, the measure becomes greater and the symptom may take place.

Acknowledhments: The authors wish to thank Drs. H. Ito, S. Watanabe and A. Watanabe for their valuable comments and Miss K. Kato for her assistance in preparing the paper. The authers also acknowledge the financial support of the Agency for Environmental Control and the Toyoda Foundation.

Reference

1) Johnson D.L., Inter-Noise 75, Sendai, 475, 1975

2) Yeowart N.S., st al., J. Acoust. Soc. Amer., 55, 814, 1974

3) Finck A.T., et al., Acoust. Soc. Amer., 33, 1140, 1961

4) Carter N.L., et al., J. Aud. Res., 2, 66, 1962

5) Mohr G. C., et al., Aerospace Med., 36, 817, 1965

6) Broner N.J., Sound & Vibr., 58, 483, 1978

7) Tempest W.(ed), Effect of Intense Infrasound on Man, London, Acad. Press, 1976

8) Harris C.S., et al., Aviat. Space Environ. Med., 47, 430, 1976

9) Slarve F.N., et al., Aviat. Space Environ. Med., 46, 428, 1975

10) Westin J.B., Aviat. Space Environ. Men., 46, 1135, 1975

Conference on
Low Frequency Noise and Hearing

7–9 May 1980
at Aalborg University Centre
Aalborg, Denmark
Proceedings edited by
Henrik Møller and Per Rubak

CHANGES IN SOME PHYSIOLOGICAL AND PHARMACODYNAMIC PARAMETERS AFTER EXPOSURE TO LOW FREQUENCY VIBRATION

A. STAN, V. VOICU, I. MAGHETI, Marilena JICUIDI, C. PAUN
Acoustical Commission of the Academy of the Socialist Republic of Romania

Summary. A series of experiments were carried out on Wistar rats exposed to low frequency vibrations in the 7-20 Hz range and pressure levels of 120-140 dB The effects of the exposure were investigated by pharmacodynamic tests, ECG recordings and follow up of behavioural changes.

Today it is common knowledge that exposure of the human body to low-frequency vibrations at levels exceeding 120 dB, generates a number of disturbances in the body functions, whose intensity is correlated to the levels of infra-sound pressure (1-6; 8; 10; 12). It is admitted that part of the disturbances observed are consequent to excessive unspecific stress of the organism; it is not, however, possible to extend this notion to the interpretation of an important number of changes in the functions of various organs and systems of the body exposed to low-frequency vibrations.

The present paper is designed to the study of some disturbances in the functions of the central nervous system and of the cardio-vascular system, as well as to the possible patho-physiological mechanisms involved in the genesis of the effects observed.

Material and methods

The experiment was carried out on Wistar rats of both sexes, weighing 160-170 g.

Exposure to low-frequency vibrations took place in a small-sized pressure chamber.

The system of emission and reception of low-frequency signals is characterized by the following data: the electric signal at the outlet of the low-frequency generator passes through the RFT LV 102 power amplifier, after which it is transmitted to an electrodynamic RFT 11075 excitator. The periodical movement of the mechanical system of the excitator is conveyed through an elastic membrane in the form of low-frequency vibrations, to the above-mentioned chamber. The reception system permits the measurement of the level of infra-sound pressure during the determinations. The acoustic signal is captured through the B and K 4146 microphone (together with the carrier frequency system 2631) and measured with a B and K 2607 amplifier and a B and K 1614 set of filters. Vibrations in the low-frequency pressure chamber were likewise mesured by the B and K accelerometers. The acceleration levels showed low vibration values, permitting delimitation of the action of low-frequency vibrations from that of the vibrations produced by the installation itself.

The animals were exposed simultaneously in lots of 6-12 to vibrations at frequencies of 7; 14 and 20 Hz and to pressure levels of 137-140 dB. They were exposed for

2-3 hours, either during single spells or during spells repeated within 24 hours. Changes in animal behaviour were cheked and the ECG recorded before and after exposure, establishing the duration of sleep, latency in the onset of the effects of pentothal and chloralhydrate, and the alterations in the specific effects of oxotremorin.

Results

The following results were obtained:

(a) In the normal animals exposed to frequencies of 7-14-20 Hz and Lp=137-140 dB, the following changes in motor activity and behaviour were recorded:
after 15-20 minutes, marked diminution in motor activity, short periods of agitation and, at the beginning of each exposure, panic and anxiety; sedation then followed and increased with the duration of exposure.

(b) After 2-3 hours exposure to 14 Hz and Lp=137 dB, pentothal administred in a dose of 70 mg/kg b.w. by i.m. route induced:

- depressive effects which were in general definetly more intense than in the non-exposed control lot; and

- increase in the effects 15 minutes after administration of the drug.

(c) Oxotremorine in a s.c. dose of 0,1 mg/kg b.w. produces in addition tremor of short duration.

- a s.c. dose of 0,2 mg/kg b.w. results in dissociation (as compared to the control lot) between tremor, exophthalmos and chromodacryorrhea;

- hypersalivation disappears and chromodacryorrhea is strongly reduced in comparison to the controls.

(d) The same experiments repeated with the same lot during two hours, five days running, produced marked sedation, the animals recovered transiently from the pentothal-induced sleep, 15-20 minutes after administration of the narcosis type lasting several hours.

(e) Oxotremorine has definitely lower effects in the exposed than in control lot.

(f) The ECG was recorded in the rats receiving chloralhydrate before and after exposure to infrasounds for 60 minutes. This lot also showed a net decrease in the heart rate and marked increase in the duration of narcosis which augmented from 45 minutes to 3-4 hours after exposure.

Discussion and conclusions

In experiments, according to various experimental models, on the effects of exposure to vibrations of different frequencies and levels, several authors noted behavioural or endocrine alterations (1-8), changes in the contractile activity of the vascular smooth muscle (6; 9; 11), heart rate disturbances, changes in blood pressure, respiratory alterations or even lethal effects (1-8; 10).

Our data furnish evidence of psycho-motor disturbances and marked sedative effects in the exposed animals.

Qualitative changes occured in depression induced by pentothal and a prolonged effect as compared to the control lot. The effects of oxotremorine were also modified quantitatively, with a net diminution in the exposed animals and dissociation between tremor, exophthalmos and chromodacryorrhea on the one hand and hyper-salivation on the other.

These changes under the influence of pentothal suggest their correlation with the functional changes brought about by infra-sound vibrations at the level of the reticular formation. Lending support to this assumption are also the data of Mayer-Schwartz and coworkers (7), which shows that sound vibrations elicit changes in the electrodermal response - a phenomenon involving the function of the activating reticular system.

Changes in the effects of oxotremorine suggest implication of the central and peripheral cholinergic system in animals exposed to ifra-sound vibrations (13).

Dissociation of the typical effects of oxotremorine also suggests the unequal influence of vibrations on the cholinergic system and other functions of the nervous system in the exposed animals.

REFERENCES

(1) C.ANITESCO, A.CONTULESCO; Arch. Malad. Profess., Med.Trav., 33, 7-8, 1972

(2) P.BORREDON, J.NATHIE: Coloq.Intern.sur les infra-sons Paris, Sept, 1973

(3) H.E. von GIERKE: - " -

(4) G.JANSEN: - " -

(5) D.L.JOHNSON: - " -

(6) B.LJIUNG, R.SIVERTSSON: Blood vessels, 12, 38, 1975

(7) M.TH.MEYER-SCHWARTZ, M.GEEER, G.MARBACH: Arch.Sci. Physiol. 22, 2 1968

(8) CH.W.NIXON: Colloq.Intern.sur les infra-sons, Paris, Sept.1973

(9) I.PYYKKÖ; J.HYVÄRINEN: Acta chirurgica Scand., suppl.465, 23, 1975

(10) L.PIMONOW: "Les infra-sons" Ed.CNRS, Paris, 1976

(11) R.SIVERTSSON, B.LJIUNG: Acta chirurgica Scand., Suppl.465, 20, 1975

(12) A.STAN: Colloq.Intern.sur les infra-sons, Paris, 1973

(13) V.VOICU, R.OLINESCU: Enzymatic mechanisms in pharmacodynamics, Abacus Press, Tunbridge Wells, 1977.

Conference on
Low Frequency Noise and Hearing

7–9 May 1980
at Aalborg University Centre
Aalborg, Denmark
Proceedings edited by
Henrik Møller and Per Rubak

THE EFFECT OF IFRASOUND ENVIRONMENT (ISE) COMBINED WITH TRANQUILIZING AGENTS ON LOCOMOTION AND CATECHOLAMINES (CA) BRAIN LEVELS OF RATS.

Papadopoulou Z., Zis B. and Ch. Spyraki

Laboratory of Experimental Pharmacology, Medical School,
University of Athens, Goudi 609 - Athens - Greece.

Sammary

The motor activity and the catecholamines (CA) brain levels of rats were determined following acute and repeated exposure to ISE or to ISE combined with tranquilizing agents as diazepam or barbiturate.

Results indicated that although the motor activity levels were decreased after acute ISE exposure and not altered after repeated one, whole brain catecholamines levels were decreased in both cases. ISE exhibited an antagonizing effect upon the depression action of tranquilizers on the locomotor activity.

Biochemical analysis showed a decrease of DA brain levels after ISE-tranquilizers combination. The NE brain levels were increased only when ISE was combined with diazepam.

The observed behavioral and biochemical changes are discussed.

INTRODUCTION

Several authors 4,5,7 have demonstrated that ISE can seriously affect human beings by provoking physiological and psychological changes.

In previous work we have shown that rats after exposure to ISE of different frequencies (2 Hz-105 dB;7Hz-122dB;16Hz-124 dB) exhibited suppressed locomotor activity 9 , impaired acquisition and retention of a conditioned avoidance response 10 and a decrease of brain Norepinephrine (NE) levels 15 .

On the other hand minor tranquilizers have long been known to provoke behavioral and biochemical changes in experimental animals 2,6, 8,11,12,13,14,16 .

The fact that minor tranquilizers are among the most widely used drugs in clinical practice and the fact that infrasounds are now very often established in every day activities, prompted this investigation.

In this work we extended the study on the effects of minor tranquilizers combined with ISE on behavioral and biochemical aspects. We have chosen as minor tranquilizers diazepam and pento barbital sodium in suitable doses and among the different frequencies of ISE studied previously, this one which provoked a more pronouced effect.

METHOD

Animals: Male and female rats of Wistar strain weighing 200±300 gr. were used. The animals were kept under standard conditions (temperature $22\pm2^{0}C$, light on between 8.00 and 20.00 hrs) and with free access to food and water. The animals were housed five per cage.

Apparatus: The apparatus used were:

1. Activity recording system (Ugo Basile, Milano, Italy), which consisted of the animal chamber and the counter and recorder incorporated into the electric unit.

2. Aminco-Bowman Spectrofluorometer (AIC).

3. ISE generation system consisting of a low voltage supply and the infrasound chamber.

Procedure:

Experiment I:Locomotor Activity

The experiment was carried out with 70 rats. They were divided into 7 groups, each containing 10 animals and receiving a different treatment. The seven formed groups were:

1. Saline (control group) 0.5 ml i.p.
2. ISE (infrasound environment)-acute exposure-(a)
3. ISE;16 Hz-124dB for one hour-repeated exposure-(b)
4. Diazepam-5 mgr/kgr i.p. (Valium-Hoffman Laroche)
5. Pentobarbital sodium-25 mgr/kgr i.p. (Nembutal-Abbott)
6. Diazepam-5 mgr/kgr i.p. + ISE;16 Hz, 124 dB for one hour
7. Pentobarbital sodium-25 mgr/kgr. i.p. + ISE;16 Hz, 124 dB for one hour.

Rats were exposed to analogous treatment once a day for four concecutive days.

The spontaneous locomotor activity was determined with the use of the Activity recording system which was located in a sound-insulated, light and temperature controlled cubicle and was carried out at the same time of the day. For each rat the number of movements during 30 min was automatically recorded on the counter. The data were printed every 5 min. so that the 30 min. session was divided into six 5-min intervals. Group 2 was tested under infrasound conditions by placing the activity cage inside the infrasound chamber. The spontaneous locomotor activity of the five remaining groups was estimated 24 hours after the last treatment in a normal environment.

The statistical analysis of the data was performed by using the t-test method.

Experiment II: Estimation of Norepinephrine and Dopamine

In this experiment as in the first one the same seven groups were formed. At the completion of locomotor activity testing, all rats were killed by cervical fracture and the brains (minus cerebellum) were rapidly taken out, weighed and immediately frozen until used. NE and DA were estimated fluorometrically by the method of Anton and Sayre 1 . The decay time of NE and DA was controlled in a series of experiments and the chosen storage time (5 days) was the same for all groups.

The statistical analysis of the data was performed by using the Student t-test.

RESULTS

1. Locomotor activity.

Motor activity levels of controls and of treated animals are depicted in Fig. 1.

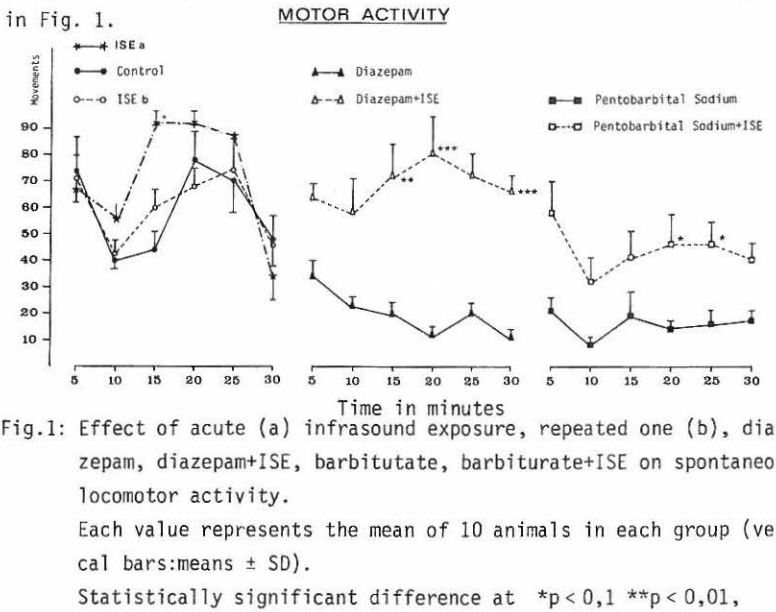


Fig.1: Effect of acute (a) infrasound exposure, repeated one (b), diazepam, diazepam+ISE, barbitutate, barbiturate+ISE on spontaneous locomotor activity.
Each value represents the mean of 10 animals in each group (vertical bars:means ± SD).
Statistically significant difference at *p < 0,1 **p < 0,01, ***p < 0,001.

Acute exposure to ISE altered the rats' motility by producing a slight increase the first 20 minutes. This increase progressively diminishes and turns to a decrease over the 30 min period, which is more pronounced at the end of a two hours session.

Repeated exposure to ISE for one hour during four consecutive days didn't affect the activity level of the experimental animals as compared to the saline group.

In contrast to diazepam or barbiturate given alone, combination with infrasounds increased the locomotor activity.

This antagonizing effect of ISE, less stronger with barbiturate than with diazepam was statistically significant.

2. NE and DA levels

Results reported on table I demonstrate that administration of diazepam or barbiturate alone produced no appreciable effect on the NE or DA levels of whole brain. ISE exposed rats displayed decrease of whole brain CA levels.

ISE-diazepam combination increased significantly the NE brain levels and decreased the DA ones. The combination of ISE with barbiturate didn't have any effect on NE concentration, but it provoked a slight increment of DA levels reduced by barbiturate given alone.

TABLE I: CA BRAIN LEVELS (in µgr/gr of brain tissue).

GROUPS	NE	DA
Controls	0.61 (±0.02)	1.11 (±0.14)
ISE	0.52 (±0.03)**	0.91 (±0.12)
Diazepam	0.60 (±0.04)	0.91 (±0.17)
Barbiturate	0.63 (±0.04)	0.80 (±0.07)*
Diazepam+ISE	0.82 (±0.03)***...	0.85 (±0.07)
Barbiturate+ISE	0.63 (±0.04)	0.84 (±0.05)*

Significantly different *($p < 0.1$) **($p=0.02$) ***($p < 0.001$) from controls; ...($p < 0.001$) from diazepam.

DISCUSSION

The results led to the conclusion that ISE may change behavioral and biochemical parameters of rats.

The acute exposure to ISE provoke during the first 20 min., an increase in locomotion, which can be associated with the novel environment. After 30 min., a period of depression-like state starts and it persists for a long time. Repeated exposure to ISE for a period of 5 days doesn't alter the activity level, which is determined in a normal environment. This fact give us the possibility to assume the hypothesis that infrasounds may have some discrete sites of action, the activation and desensibilization of which, could be relatively responsible for this dual effect.

The formulated hypothesis of discrete sites of action of infrasounds may also be supported by our results on the combination of ISE with pharmacological agents. It is now well established that minor tranquilizers, especially benzodiazepines act via their own receptors 3 . The suppressed locomotion by the minor tranquilizers is restored when the two substances are combined with ISE. Is this an antagonizing effect excerced via a common site of action, or simply ISE does establish a very strong stress, which cannot be affronted by minor tranquilizers?

The behavioral changes seen correlate with the biochemical results. The increase in NE levels after ISE-diazepam treatment may be associated with the behavioral "excitation" which is more pronounced in Diazepam-ISE combination than in ISE-barbiturate one.

We don't expect to infer clinical implication from our findings or to involve the emerged hypothesis in an explanation of a mechanism of action. We want only to notice that ISE provoke behavioral and biochemical changes underlaying CNS activity and that an antagonizing effect upon minor tranquilizers action exists.

REFERENCES

1. ANTON, A. and SAYRE, D.: A study of the factors affecting the aluminum oxide Trihydroxyindole procedure for the analysis of catecholamines.J.Pharmac.exp.Ther.138, 360 (1962).

2. BIGNAMI, G., DE AGETIS, L. and GATTI, G.L.: Facilitation and impairment of avoidance responding by performance baselines.J.Pharmacol. Exp.Ther. 176, 725-732 (1971).

3. BRAESTRUP, C. and SQUIRES, R.F.: Specific benzodiazepine receptor in rat brain characterized by high affinity ^{3}H-diazepam binding Proc. nat.Acad.Sci,(Wash.), 74, 3805-3809 (1977).

4. BROWN, R.: What levels of infrasound are safe? New Scient.60,414(1973)

5. BRYAN, M.: Does infrasound make drivers drunk? New Scient.53,584(1973)

6. COLE, H.F. and WOLF, H.H.: The effects of some psychotropic drugs on conditioned avoidance and aggressive behavior. Psychopharmacologia 8, 389-396 (1966).

7. EVANS, M. and TEMPEST, W.: Some effects of infrasonic noise in transportation.J.Sound.Vibrat.22, 19-24(1972).

8. LIDPRINK, P., CORRODI, H., FUXE, K., OLSON, L.: The effects of benzodiazepines, meprobamate and barbiturates on central monoamine neurons In: The benzodiazepines, edited by S.Garattini E.Mussini and L.O. Randell p.203 Raven Press-New York.

9. PETOUNIS, A., SPYRAKI, Ch., VARONOS, D.: Infrasound effects upon activity levels of rats. Physiol. Behav. 18, 153-157 (1977a).

10. PETOUNIS, A., SPYRAKI, Ch., VARONOS, D.: Effects of infrasouds on the conditioned avoidance response.Physiol.Behav.18, 147-152 (1977b).

11. RASTOGI, R.B., AGARWAL, R.A., LAPIERR, Y.D., SINGHAL, R.L.:Effects of acute diazepam and clobazam on spontaneous locomotor activity and central amine metabolism in rats. European Journal of Pharmacol. 43, 91-98 (1977).

12. SANSONE, M.: Benzodiazepines and amphetamine on avoidance behaviour

of mice.Arch.int.Pharmacodyn. 218, 125-132 (1975).

13. SANSONE, M.: Effects of Chlordiazepoxide-Scopolamine combinations on shuttle-box avoidance performance of mice. Arch.int.Pharmacodyn. et de Ther. 235, 1, 93-102 (1978a).

14. SANSONE, M., RENZI, P.: Facilitating effects of Chlordiazepoxide on the performance of mice in an inhibitory avoidance task. Psychopharmacology 59, 161-163 (1978b).

15. SPYRAKI, Ch., PAPADOPOULOU, Z., PETOUNIS, A.: Norepinephrine levels in Rat brain after infrasound exposure. Physiol. Beh. 21, 447-448 (1978).

16. STEIN, L., WISE, D., BELLUZZI, J.: Neuropharmacology of reward and punishment In: Handbook of Psychopharmacology Vol 8. Edited by Iversen L.L., Iversen, S.D. and Snyder, S.H., Plenum press. New-York and London p.25(1977).

Conference on
Low Frequency Noise and Hearing

7–9 May 1980
at Aalborg University Centre
Aalborg, Denmark
Proceedings edited by
Henrik Møller and Per Rubak

Cochlear microphonic potential and intracochlear sound pressure measurements at low frequencies in guinea pigs.

R. Franke and A. Dancer
members of the Physiology group of the French-German Research Institute
12, rue de l'Industrie, 68301 Saint-Louis, France

Summary

The study of microphonic potential and intracochlear sound pressure in guinea pigs seems to show that the behaviour of the cochlea at very low frequencies is controlled by three discrete elements:

- the compliance of the whole basilar membrane
- the acoustic resistance of the helicotrema
- the compliance of the round window.

The part of each of these elements has been established.

The compliance of the whole basilar membrane produces constant amplitudes at frequencies lower than the minimum frequency at which a travelling wave is present (130 Hz).

In fact, this constant amplitude range is limited by connection of the two cochlear scalae through the helicotrema resistance.

This protecting mecanism produces an attenuation slope for frequencies lower than 80 Hz.

The compliance of the round window does not modify the slope of cochlear microphonic, but it induces a constant sound pressure in scala tympani at any frequency.

Decreasing of the sound pressure in scala vestibuli is therefore limited, for frequencies less than 25 Hz, by this constant value of the sound pressure in scala tympani.

It is obvious that further measurements, especially of intracochlear sound pressure, will be necessary to confirm these first results and to estimate to which extent our hypotheses are right.

1. Introduction

Previously conducted experiments [1] have shown that the differential cochlear microphonic potential as well as the differential sound pressure across the basilar membrane are closely related and also well correlated with the sensitivity curve [2] (fig. 1).

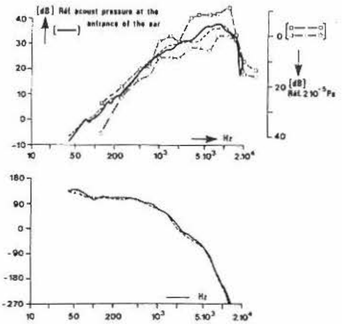


Fig. 1. Comparison between :
- cochlear microphonic in the first turn (---, arbit. amplit. ref.)
- sound pressure between the vestibular and the tympanic scalae (—)
- hearing sensitivity levels according to Prosen [2] (o-·-o albinos □--□ pigmented)
in guinea pigs versus frequency.

At low frequencies, presently our domain of interest, it is well known that the compliance of the bulla governs the displacements of the tympano-ossicular chain, inducing a 6 dB/oct. slope below 2 kHz [3].

At very low frequencies, below about 100 Hz, two other mecanisms at least seem to play a role (fig. 2):

a) the compliance of the membrane of the round window

b) the helicotrema which decreases the differential sound pressure because of the communication between the two scalae.

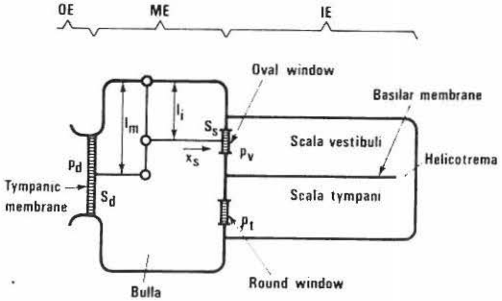


Fig. 2.

Schematic of the mechanic of the ear.

Moreover, taking into account the values of the propagation delays of the travelling wave along the basilar membrane [1,4], we can calculate the maximum wavelength spreading over the whole basilar membrane. This wavelength corresponds to about 550 Hz. For frequencies well below 550 Hz, all the points of the basilar membrane are believed to vibrate in phase. Thus we can consider the cochlea to be a physical system which no longer consists of distributed elements, but which is formed of lumped elements. The frequency range over which transition from distributed elements system to lumped elements system occurs, can be brought together with the minimum best frequency of a unit fibre recorded in the guinea pig: 100 Hz [5].

At frequencies less than 100 Hz there is no tonotopic effect. Moreover the auditory sensitivity will probably have vanished.

2. Experiment

2.1. Methods

Acoustic stimuli (pure tones) are delivered by a closed acoustic system driven by a condenser microphone (fig.3). When a constant voltage is applied to this system, it behaves like a constant volume displacement source or an injector of volume velocity which increases proportionately to the

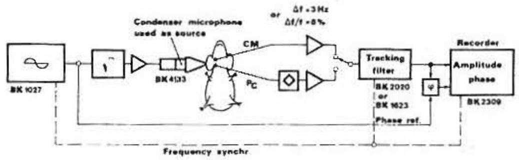


Fig. 3.

Block diagram of the apparatus.

frequency (6 dB/oct.). Thus, at low frequencies, the displacements of the tympano-ossicular chain are analogous to those induced by a constant acoustic pressure at the tympanum with the bulla closed.

The differential electrodes and the pressure probe are fixed into the first cochlear turn.

The signals are amplified and applied to a narrow band tracking filter. Both amplitude and phase are recorded as a function of the stimulus frequency.

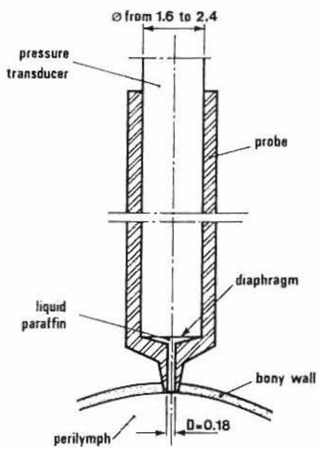


Fig. 4. Schematic diagram of the implanted pressure microphone.

Fig. 4 shows the pressure transducer with its probe inserted into the bony wall of the cochlea. The transducer is of the piezoresistive type with a Wheatstone bridge diffused into the silicon membrane. The probe is filled with silicon fluid of fitted viscosity in order to realize the adaptation between perilymph and the transducer membrane.

The inner diameter of the probe is 0.18 mm at the tip and, especially, for low frequencies, its input impedance is much higher than that of the oval window.

The probe is inserted into the scala vestibuli of the first turn (cross area: 0.4 mm^2 [6]) without destroying the Reissner's membrane.

2.2. Results

Figure 5 shows amplitude and phase of the differential cochlear microphonic and of the sound pressure in scala vestibuli of the first turn as a function of frequency.

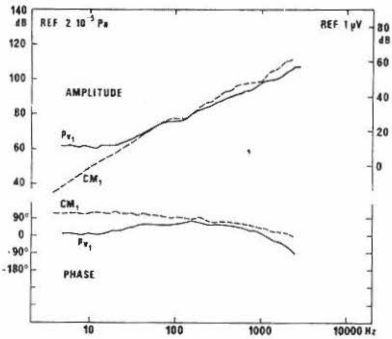


Fig. 5. Amplitude and phase of the differential microphonic potential (CM_1) and the sound pressure in the scala vestibuli (p_{v1}) recorded in the 1st turn of the cochlea versus frequency.

This figure illustrates the mean results recorded in 7 guinea pigs for the cochlear microphonic. Because of an early failure of the pressure transducer, sound pressure has been recorded in 2 guinea pigs only. It should be noted that the amplitude curves have many common characteristics: the slope of about 6 dB/oct is broken at about 100 Hz by a small plateau previously described by DALLOS [7].

On the other hand there is an important difference at very low frequencies ($f \leq 25$ Hz): the amplitude of the cochlear microphonic decreases at 6 dB/oct whereas the amplitude of the sound pressure remains constant. Simultaneously the 90° phase lead of the sound pressure disappears.

Thereafter we made several modifications at the mechanical configuration of the cochlea and we observed the changes occurring at the level of the cochlear microphonic and sound pressure.

Figure 6 shows the cochlear microphonic in one guinea pig before modifying the configuration. The response of the untouched cochlea is similar to the mean curve of the preceding figure.

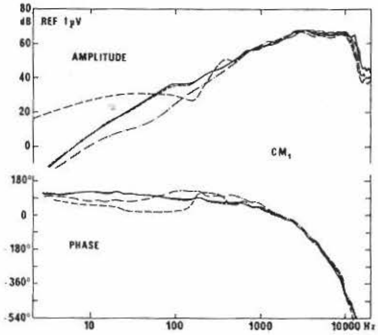


Fig. 6. Typical CM_1 response versus frequency :

——— *intact cochlea*

..... *after drilling a hole (diam. 0.6 mm) into the 1st turn of scala tympani*

—·— *after drilling a hole (diam. 0.6 mm) into the 4th turn of scala vestibuli*

– – – *after sealing of 4th turn.*

When a hole of about 0.6 mm in diameter is drilled into the scala tympani of the first turn, the response remains unchanged.

When the same hole is drilled into the scala vestibuli at the apex we can observe a decrease of the cochlear microphonic amplitude at frequencies below 700 Hz (maximum attenuation: 14 dB at 60 Hz). Finally, we sealed the apex and the 4th turn by injecting silicon paste into the hole drilled at this place. Now the amplitude of the cochlear microphonic remains approximately constant for frequencies below 100 Hz and there is a phase lag of 90° with respect to the original response at the same frequencies. When the frequency increases, the amplitude curve rejoins the original curve after a few oscillations of decreasing amplitude.

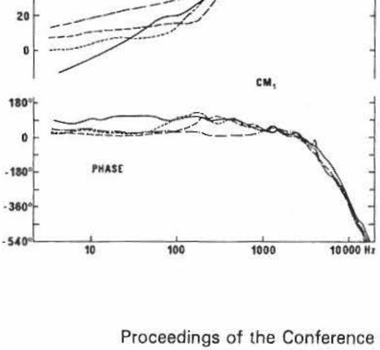


Fig. 7. Typical CM_1 response versus frequency:

——— *intact cochlea*

----- *after sealing of 4th turn*

– – – *after sealing of 3rd turn*

—·— *after sealing of 2nd turn.*

Figure 7 shows the results obtained on one guinea pig when the cochlea is sealed at different levels. Successive sealing of the 4th, 3rd and 2nd turn induces low-frequencies constant responses which tend towards higher frequencies before rejoining the original curve. Simultaneously the 90° phase lag with respect to the initial phase tends more and more to the higher frequencies.

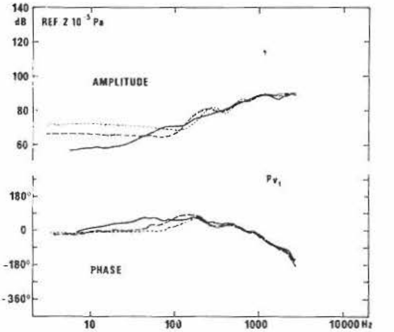


Fig. 8. Typical p_{v1} response versus frequency:
——— *intact cochlea*
------ *after sealing of 4th turn*
— — — *after drilling a hole (diam. 0.4 mm) into the 1st turn of scala tympani.*

Figure 8 shows the changes occurring in sound pressure following the same modifications of the cochlea. As far as the cochlear microphonic is concerned, sealing the 4th turn induces a constant amplitude at low frequencies ($f \leq 140$ Hz). The curve rejoins the original curve after a few oscillations of decreasing amplitude. In the same way the phase lead desappears at low frequencies.

When a hole (diameter 0.4 mm) is drilled into the scala tympani of the first turn, the amplitude of the plateau decreases by 5 to 6 dB.

3. Discussion

All these results can be easily explained in considering the electrical analog of the auditory receptor driven by the condensator microphone (fig. 9).

In a first approximation let us neglect the nearly constant leakage volume displacement (x_1) and the reactive term of Z_H (a calculation based on anatomical measurements [7] shows

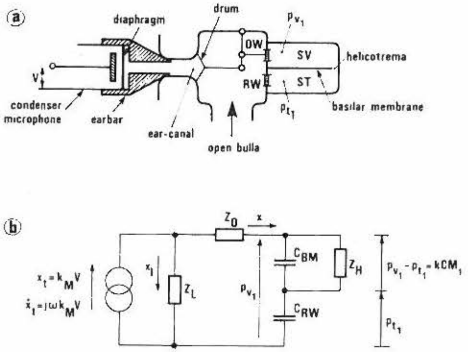


Fig. 9. Simplified diagram of the acoustic stimulation of the auditory receptor (a) and the low frequency electric analog (b).

V : alternate voltage applied to the microphone
k_M : constant factor due to microphone characteristics
Z_L : leakage acoustic impedance including :
- the compliance of the membrane of the microphone
- the compliance of the air volume in the earbar and in the ear-canal
- the impedance of the portion of the tympanum not rigidly coupled to the ossicles [8]
Z_O: acoustic impedance of the ossicles including the oval window
Z_H: acoustic impedance of the helicotrema (including the impedance of the scalae)
x_t: total volume displacement of the membrane of the microphone
x_l: leakage volume displacement
x : volume displacement injected into the cochlea
p_{V1}: sound pressure in the 1st turn of scala vestibuli
p_{T1}: sound pressure in the 1st turn of scala tympani
CM_1: differential cochlear microphonic potential in the first turn
k : constant factor.

this approximation to be valid for $f<300$ Hz).

If we suppose that the cochlear microphonic (CM_1) is proportional to the displacements of the basilar membrane and that the displacements of this membrane are proportional to the differential pressure ($p_{V1}-p_{V2}$), we easily obtain the following results (fig.10): Volume displacement of the oval window being kept constant versus frequency, sound pressure in scala tympani of the first turn is also constant. In effect, the round window can be regarded as a pure compliance.

CM_1 which is proportional to the differential pressure, is also constant in the frequency range over which the compliance of the basilar membrane predominates ($f>f_2$), but it increases proportionately to the frequency when the leakage resistance of the helicotrema (R_H) is predominant ($f<f_2$).

It should be noted that this protecting mechanism is

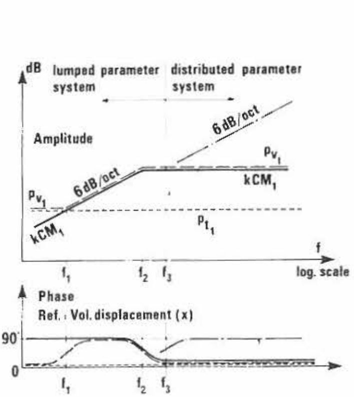


Fig. 10. Schematic diagram resulting of the electric analog of fig. 10b.

different from the one proposed by DALLOS [7] who has assumed that the input impedance of the cochlea <u>without</u> the contribution of the helicotrema remains resistive even at low frequencies.

The sound pressure in the scala vestibuli (p_{V1}) is the sum of the sound pressure in the scala tympani (p_{V1}) and of the sound pressure difference beween the two scalae ($p_{V1}-p_{V2}=k\,CM_1$) ; for this reason, sound pressure in scala vestibuli has the same behaviour than the CM_1 excepted at very low frequencies ($f<f_1$) at which it cannot be smaller than p_{t1}.

This can be applied to frequencies which are low enough for neglecting propagation phenomena. If this is not the case ($f>f_3$), the cochlea cannot be considered to consist of lumped parameters, but to be formed of distributed parameters, forming an acoustic transmission line.

The input impedance of such a line is its characteristic impedance which, for a low-loss line, is nearly purely resistive (in fact, the input impedance of the cochlea is purely resistive at medium frequencies [1]).

In that case, p_{V1} as well as CM_1, will increase proportionately to frequency.

If the input resistance of the cochlea is lower than the resistance of the helicotrema, amplitude shift will occur between the two straight parts of the curve which have slopes of 6 dB/oct, and coincide with a plateau ($f_2<f<f_3$) (fig.10).

Comparing this to the amplitude and phase recording of CM_1 and p_{V1}, we can observe a good agreement (fig.5).

If we switch off Z_H (fig. 9b), the constant amplitude between f_2 and f_3 will be extended to the lower frequencies, in approximately the same manner than that observed for CM_1 and p_{v1} recordings with the 4th turn sealed (fig.6 & 8). In the same way, it is easy to show that by shunting C_{BM} and C_{RW} we obtain an amplitude decrease as we have observed on CM_1 recording with opened scala vestibuli (fig. 6). For Z_H switched off, a successive reduction of the value of C_{BM} in the electric analog allows to obtain low frequency constant responses, which tend toward higher frequencies before rejoining the original curve, in the same way as those obtained by sealed 4th, 3rd and 2nd turns. The same phase modifications can also be observed (fig. 7).

Finally, the shunting of C_{RW} allows to reduce p_{t_1} and consequently p_{v_1} but not $k\,CM_1$, according to the recordings obtained after drilling holes at the basal end of the scala tympani (fig.8 & 6).

A certain quantitative confirmation can be found by the calculation of the resistance of the helicotrema.

With the transition frequency f_2 (fig.10), which is about 80 Hz (fig. 5), and the compliance of the whole basilar membrane computed with ZWISLOCKI's formula [4], we can determine the resistance of the helicotrema. We have found $R_H = 1/2\pi f_2 C_{MB} = 0.8 \cdot 10^{10} Ns/m^5$, and this value is in the same range than the one obtained by DALLOS [7]: $1.25 \cdot 10^{10} Ns/m^5$ from anatomical measures.

In another way, a measure based on a artificial perilymph flow through the helicotrema is being performed and should allow to determine this value more exactly.

4. Conclusions

The study of cochlearmicrophonic potential and intracochlear sound pressure in guinea pigs seems to show that the behaviour of the cochlea at very low frequencies is controlled by three discrete elements:

- the compliance of the whole basilar membrane
- the acoustic resistance of the helicotrema
- the compliance of the round window.

The part of each of these elements has been established:

The compliance of the whole basilar membrane produces constant amplitudes at frequencies lower than the minimum frequency at which a travelling wave is present ($\simeq$130 Hz).

In fact, this constant amplitude range is limited by connection of the two cochlear scalae through the helicotrema resistance.

This protecting mechanism produces an attenuation slope for frequencies lower than about 80 Hz.

The compliance of the round window does not modify the slope of cochlear microphonic, but it induces a constant sound pressure in scala tympani, at any frequency.

Decreasing of the sound pressure in scala vestibuli is therefore limited, for frequencies less than 25 Hz, by this constant value of the sound pressure in scala tympani.

It is obvious that further measurements, especially of intracochlear sound pressure, will be necessary to confirm these first results and to estimate to which extent our hypotheses are right.

References

[1] DANCER A.L., FRANKE R.B.,
Intracochlear sound pressure measurements in guinea pigs
Hearing Research to be published (1980).

[2] PROSEN C.A., PETERSEN M.R., MOODY D.B., STEBBINS W.C.,
Auditory thresholds and kanamycin - induced hearing loss in the guinea pig assessed by a positive reinforcement procedure
J. Acoust. Soc. Am. 63, 559-566 (1978).

[3] MUNDIE J.R.,
The impedance of the ear, a variable quantity.
Middle ear function sem. Rep.n° 576, US Army Med. Res. Lab. Ft. Knox, Kentucky, 63-85 (1962)

[4] ZWISLOCKI J.J.,
Cochlear waves: interaction between theory and experiments.
J. Acoust. Soc. Am. 55, 578-583 (1974)

[5] EVANS E.F.,
Personal communication.

[6] FERNANDEZ C.,
Dimensions of the cochlea (Guinea pig)
J. Acoust. Soc. Am. 24, 519-523 (1952).

[7] DALLOS P.,
Low-frequency auditory characteristics: species dependance
J. Acoust. Soc. Am. 48, 489-499 (1970).

[8] ZWISLOCKI J.,
Analysis of the middle ear function. Part II: guinea pig ear
J. Acoust. Soc. Am. 35, 1034-1040 (1963).

Conference on
**Low Frequency Noise
and Hearing**

7–9 May 1980
at Aalborg University Centre
Aalborg, Denmark
Proceedings edited by
Henrik Møller and Per Rubak

LOW FREQUENCY MODELS FOR MECHANICAL TO NEURAL TRANSDUCTION

Per Rubak
Institute of Electronic Systems
Aalborg University Center
Box 159, DK-9100 Aalborg
Denmark.

SUMMARY

A brief introduction to transmission of sound through the middle ear and the inner ear is given. A short review of the Schroeder/Hall model for mechanical to neural transduction and a discussion of the adequate stimulus is included. Computer calculations of the firing pattern for tone bust stimulation with fundamental frequencies 10 Hz, 20 Hz and 100 Hz is presented. The Calculation is performed at levels 80 dB, 70 dB, 60 dB and 40 dB. Finally the results are compared with results from animal experiments.

An important step in auditory analysis is through models and experiments to determine the firing pattern of the fibers in the cochlear nerve (CN) with a given sound stimulation. The firing pattern in CN is the primary input to the information processing part of the auditory system which on human beings can be studied by means of psychophysical methods. The conclusions drawn through psychophysical experiments could in my opinion often be improved if the results are combined with consideration of the firing pattern in CN.

The transduction from sound pressure to nerve spikes in the cochlear nerve can be divided into three parts:

a) Middle ear transmission
b) Inner ear transmission: displacement of stapes to vibration pattern of the basilar membrane
c) Hair-cell trancduction: mechanical deformation to generation of nerve spikes

a) Middle ear transmission.

At low frequencies the middle ear transmission can be modelled by a reasonable approximation - as a simple 2. order low-pass filter:

$$\frac{x_0}{p_0} \cong \frac{A\omega_0{}^2}{(j\omega)^2 + (j\omega)\cdot\alpha\cdot\omega_0 + \omega_0{}^2} \tag{1}$$

x_0 displacement of stapes

p_0 sound pressure at ear drum

ω_0 resonance frequency (undamped)

α damping constant

A gain at low frequency (below about 300 Hz)

Below about 300 Hz (1) could be reduced to: $\frac{x_o}{p_o} \simeq A$ (2)

Equation (1) is only a reasonable approximation as long as the transmission is linear. The linearity assumption seems to be valid up to about 110 dB if the stapedius reflex is not activated. Preliminary experiments suggest that the reflex normally first is activated above 120 dB at 20 Hz. Abnormalities in the middle ear can lower this limit considerably.

b) Inner ear transmission.

The one dimensional fluid dynamic model described by Zwislocki [1], which gives a travelling wave as solution, seems to be a reasonable starting point when modelling the vibration pattern of the basilar membrane. This model has to be modified to include the effects of Helicotrema and the Round Window at low frequencies. It is possible also to solve this problem by means of analytical expressions if some reasonable approximations is done, see [2]. The numerical evaluation of these expressions is not finished, therefore a conclusion cannot be given.

At low frequencies the selectivity measured in a single auditory nerve fibre and the selectivity of the basilar membrane considered as a hydro-mechanical filter seems to be in reasonable agreement with each other. Therefore the so called "second filter" is probably not important at low frequencies which give simpler conditions for studying the mechanical to neural transduction.

c) Hair-cell transduction.

The model introduced by Schroeder and Hall [3] seems to be very profitably because it has a reasonable physiological background and because the model is in agreement with many of the neurophysiological experiments concerning the firing pattern of the auditory nerve.

The basic ideas in the model are

1) Neurotransmitter (NT) in the hair-cell is produced with a fixed average rate r quanta/sec.

2) NT is released and cause the nerve fibre to generate spikes with a probability per unit time, $f(t) = n(t) \cdot p(t)$ where
$n(t)$ number of NT quanta in the hair cell at time t
$p(t)$ "permeability" function which is related to the "mechanical" stimulation, $s(t)$, of the hair cell

3) Quanta disappear independently of stimulation and without causing nerve firings with a probability per unit time = $g \cdot n(t)$.

It is proposed that the permeability function should be given by:

$$p(t) = p_0\{\tfrac{1}{2}\, s(t) + [1 + \tfrac{1}{4}\, s^2(t)]^{\frac{1}{2}}\} \qquad (3)$$

p_0 is a constant related to the spontaneous firing rate (without stimulation) of the nerve.

The rules 1 to 3 can easily be combined to give the following equation to determination of $n(t)$:

$$\frac{dn(t)}{dt} = r - n(t)\,[p(t) + g] \qquad (4)$$

Adequate stimulus

Schroeder and Hall suggest that the stimulus $s(t)$ is proportional to the vibration amplitude $y(x,t)$ of the basilar membrane at the location of the hair-cell.

This is an open question, maybe also the pressure p(x,t) and the partial derivatives play a significant role. However, at low frequencies y(x,t) seems to be the most important single parameter and therefore a reasonable starting point.

The relation between the pressure at the ear drum p_0 and the displacement of the basilar membrane at the actual hair-cell position should also be known for calculation of s(t) when the pressure at the ear drum is given.

Simulation of Schroeder/Hall model at low frequencies

The nonlinear differential equation (4) can be solved analytical, see [4]. A numerical calculation of this equation has been performed on a digital computer at the frequencies: 10 Hz, 20 Hz and 100 Hz.

The applied input function, s(t) was a tone bust. As pointed out earlier a more appropriate input function would be the basilar-membrane respons to a tone-burst sound pressure stimulation at the ear drum, but this is left for future work.

All computer calculations were done with the following values for the model-constants:

$r = 150/\text{sec}$
$g = 33/\text{sec}$
$p_0 = 17/\text{sec}$

This corresponds approximately to an "adaptation time constant" τ = 20 mS. The stimulation function s(t) is normalized such that $\overline{s^2(t)} = 1$ corresponds to a sound pressure level of 30 dB re 20 µpa.

The calculations have been performed at the following levels: 40 dB, 60 dB, 70 dB and 80 dB.

Results:

The results are plotted in figures 1 to 3.

Considering the respons at 100 Hz shown in fig. 1 it is seen that an initial overshoot is present at 70 dB and 80 dB. It should also be noticed that the adaption only covers about one period of the fundamental frequency in the tone bust.

When the frequency is lowered to 20 Hz, fig. 2, it is notable that the initial overshoot only is present at 80 dB level (and above).

Finally at 10 Hz, fig. 3, it is seen that the usual overshoot is reversed to an undershoot.

Discussion:

In fig. 4 (from ref. [5]) is shown firing probability (xenopus laevis) for combined mechanical and electrical stimulation. This experimental result seems to be in reasonable agreement with the Schroeder/Hall model. Fig. 5 (from ref. [6]) shows the firing probability (200 Hz) in a fibre (cat), this seems also to be in reasonable agreement with the theory.

References:

[1] Zwislocki, J.: J. Acoust. Soc. Amer., 1950, v.22, 778-784.
[2] Rubak, P.: Symposium on Low Frequency Noise, Chelsea College, London, 1979.
[3] Schroeder, M.R., Hall, J.L.:Facts and Models in Hearing. Springer Verlag, 1974.
[4] Schroeder, M.R. Proceedings of the IEEE, Vol. 63, No. 9, 1975.
[5] Honrubia V. et.al. Ann. Otol., Vol. 85, p. 697, 1976.
[6] Zwicker, E.: J. Acoust. Soc. Amer. Vol. 59, p. 166, 1976.

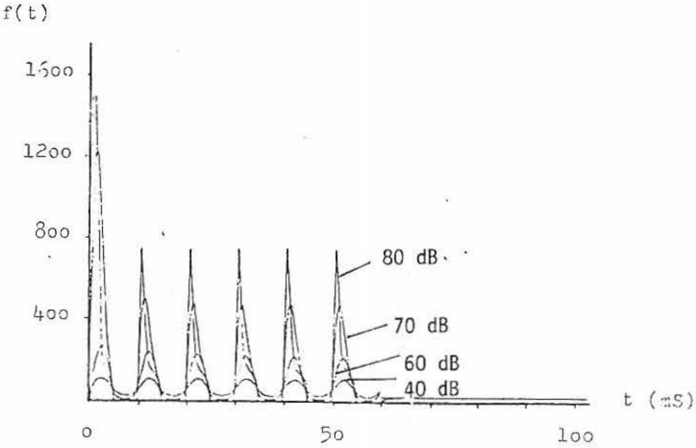


Fig. 1. Firing probability for tone burst duration 60 mS and fundamental frequency 100 Hz.

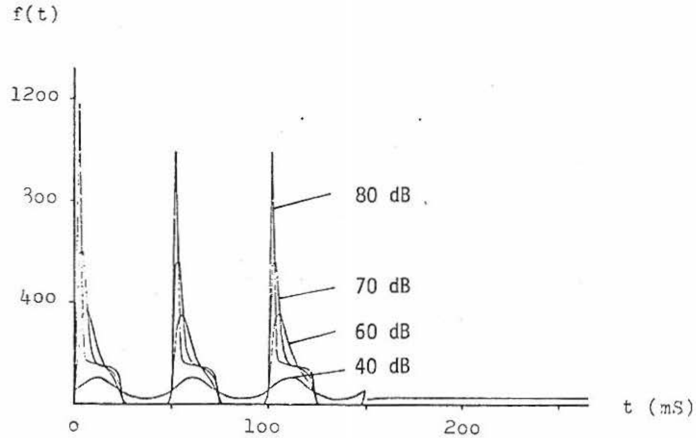


Fig. 2. Firing probability for tone burst duration 150 mS and fundamental frequency 20 Hz.

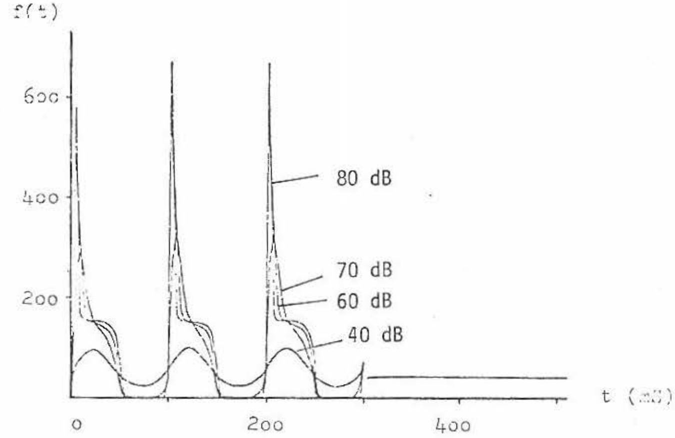


Fig. 3. Firing probability for tone burst duration 300 mS and fundamental frequency 10 Hz.

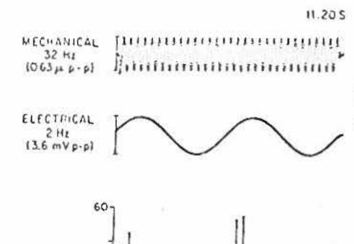


Fig. 4. Neural response of a fibre innervating the Xenopus laevis lateral line organ in response to the combination of mechanical and electrical stimuli.

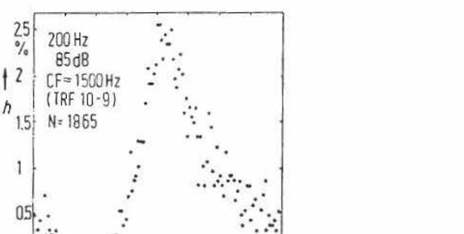


Fig. 5. Period histogram, $h(t)$, produced by a 200-Hz 85-dB pure tone stimulus observed in a single auditory nerve fiber of a cat. The sine wave below the histogram corresponds to the stimulus (rarefaction, $-p$, as function of t) calculated from data given by Dr. Pfeiffer.

Conference on
Low Frequency Noise and Hearing

7–9 May 1980
at Aalborg University Centre
Aalborg, Denmark
Proceedings edited by
Henrik Møller and Per Rubak

Infrasound in ventilation plants

Stefan Einarsson, Ingemansson Acoustics, Box 53037,
S-400 14 Göteborg, Sweden

Summary

This paper describes an approach to finding ways to avoid or reduce infrasound from ventilation plants by studies in existing buildings.
An important part of the study is finding a reference for normal ventilation infrasound level, the mean value for 32 comparable locations is shown.
It seems to be possible to find signifiant variation in infrasound level between different types of systems, although the statistic material must be increased before drawing final conclusions.
The reproducibility between measurements at different times seems to be excellent.
For one case it is shown that the infrasound level is dominated by a supply fan.

Background

We have, as acoustics consultants, had an increasing number of cases indicating that low frequency noise or infrasound is causing annoyance - even at such levels which are usual in buildings equipped with mechanical ventilation systems. We all know that noise in the octave bands 31.5 and 63 and 125 Hz causes more annoyance than indicated by common criteria expressed in A-weighted sound level but we believe that the infrasound area also must be taken into careful consideration.
One must realise that adequate criteria for long time exposure to infrasound are yet far from known. Nevertheless it seems necessary to begin studying the problem with the aim to eventually find means to reduce or avoid infrasound - as being in any case unwanted.

This paper describes an approach to seek answers to the following questions:

- What are normal infrasound levels from ventilation plants?
- Do these levels vary between different buildings with different system data?
- How do the levels change from time to time and from one location to another?
- Is it possible to point out special infrasound sources?

Our approach is to do studies in existing buildings and in fact many of the questions above can only be answered that way. Other questions can alternatively be answered by laboratory studies on systems, or rather parts of systems, but then the risk exists that problems, involving the system as a whole, get lost.

We regard the study presented here as the pilot part of a bigger investigation giving broader statistic material and reliable conclusions. This study has been sponsored by the Swedish Council for Building Research and is carried out in cooperation with the Gothenburg branch of AxRo Consult AB, a ventilation consultant firm.

Measuring and analysing technique

The procedure of measurement, instrumentation and analysis is further described and discussed in another paper at this conference (J. Svensson, S. Tyrland). We here only state some important details on this matter:

- Reproducible microphone position - room corner
- Tape registration and storing for repeated analysis of the signal if new criteria show up
- Narrowband analysis (FFT power spectrum) - rms value over sufficient length of time (3 minutes). Resolution 0.156 Hz, corresponding to analogue bandwidth of about 0.5 Hz.

Fig. 1 shows overall frequency response and noise floor of the system used.

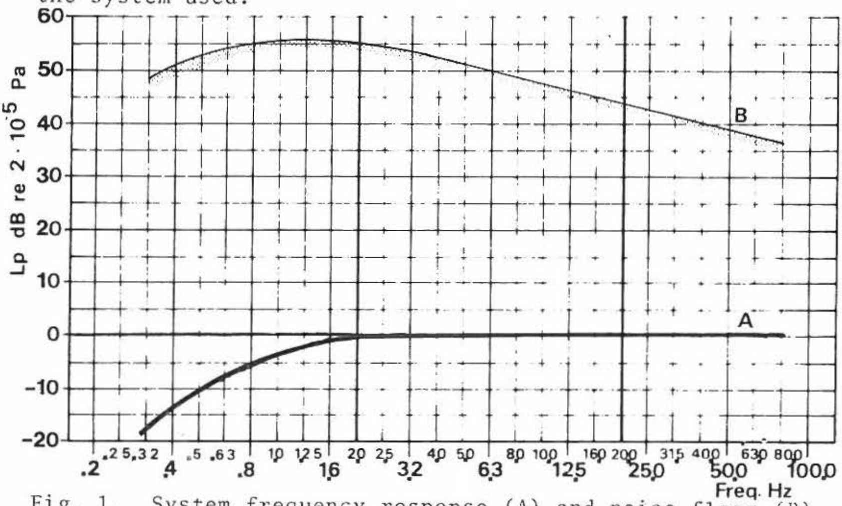


Fig. 1. System frequency response (A) and noise floor (B)

Measuring results

Sofar we have made measurements in some 50 locations in 10 buildings. Of these we have chosen 32 locations in 9 buildings, analysed by same technique and representing rooms of similar size. In all these cases measurements have been made both with and without the ventilation system in function. Fig. 2 shows the envelope of all 32 measurements together with a plot of the mean level and system noise floor.

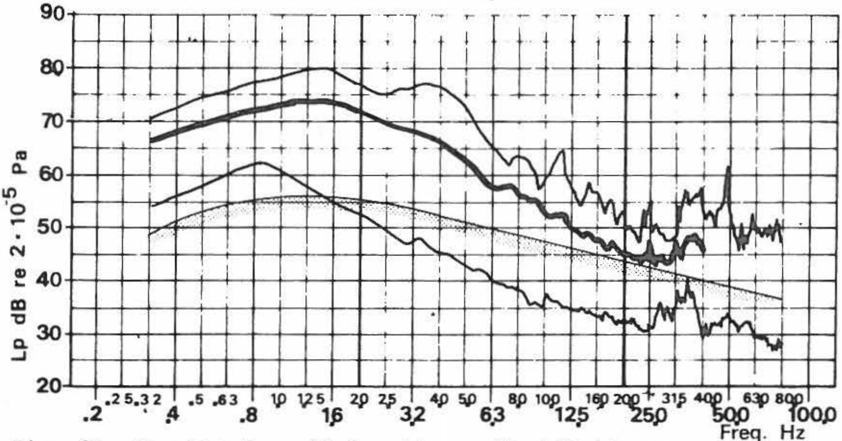


Fig. 2A. Results from 32 locations. Ventilation on

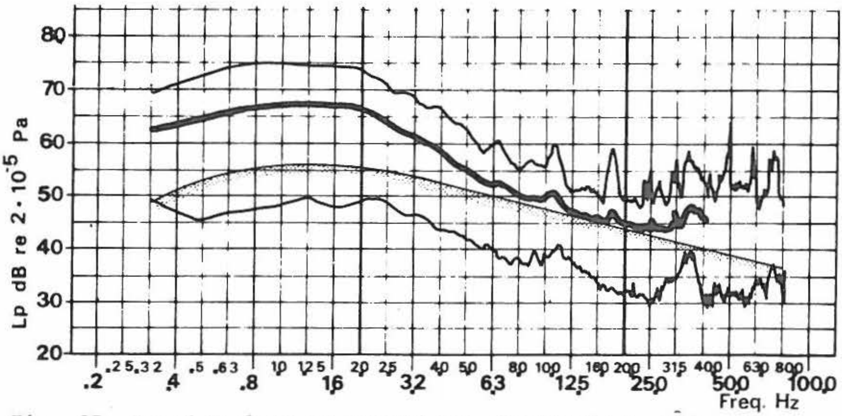


Fig. 2B. Results from 32 locations. Ventilation off.

We can see that the spread between the different measurements is substantial in both "on" and "off" cases. We also note that levels below the system noise floor occur. This depends upon a technical fault in an amplifier which happened during the measuring phase and was discovered first after the evaluation. We though believe that all significant levels lie above the later floor (shown curve).
The mean level shown in fig. 2A can, for the time being, be regarded as "average ventilation infrasound level", in terms of power spectrum (resolution 0.156 Hz, bandwidth approx 0.5 Hz) for normal office rooms. Of course this reference must be adjusted to broader statistic base.

If we study the "on" and "off" cases in one location we typically find what is shown in fig. 3.

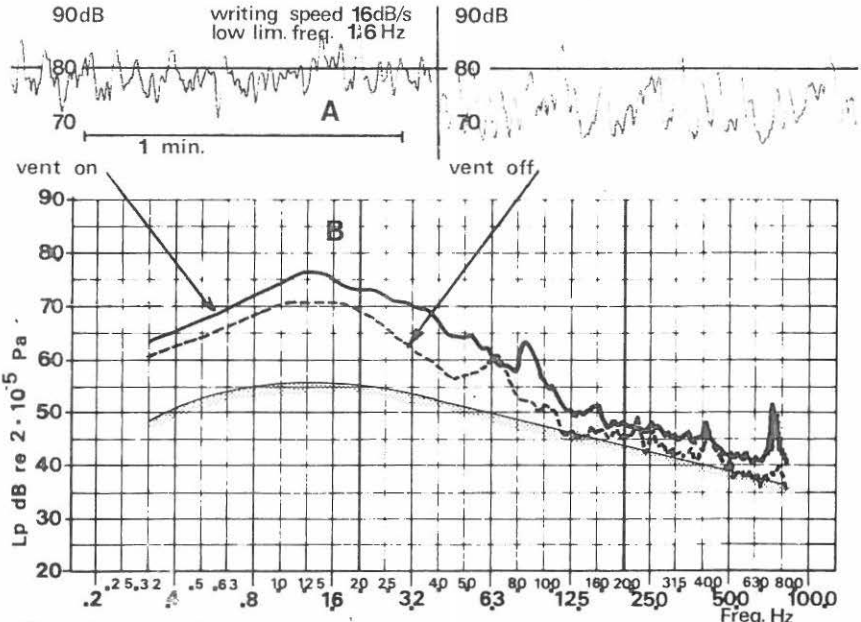


Fig. 3. Broadband levels v.s. time (A) and narrowband levels v.s. frequency (B).

The broadband level is determined by the level in the lowest frequency region but nevertheless there is some interesting information in the time graph. For example one can see that peak values are almost the same in both cases indicating that these originate from people moving around in the building rather than the ventilation plant. This is also confirmed by measurements made in empty buildings after working hours.

When studying the results from one building we find that the levels vary from room to room and these variations may overlap the differences between one building and another. Nevertheless one might study the mean values from different buildings and different types of ventilation systems.

Without first studying the results, we asked the cooperating ventilation consultant to categorize the systems in terms of ventilation technique. He came up with the following:

1. Old systems with poor ventilation degree (2 buildings)
2. Normal modern systems with ventilation degree according to modern standards. These should be divided into two subgroups:
   - A: Ducts for both inlets to and outlets from the rooms (2 buildings)
   - B: Outlets from the rooms through openings in corridor wall (3 buildings)
3. Semi modern system with very big central fans, more complex than todays standard (1 building).

Fig. 4. shows the mean levels from these categories and as one can see there really exists significant difference between the different cases. In fact the variations between the buildings within each category are fairly small compared with the differences shown in fig. 4.

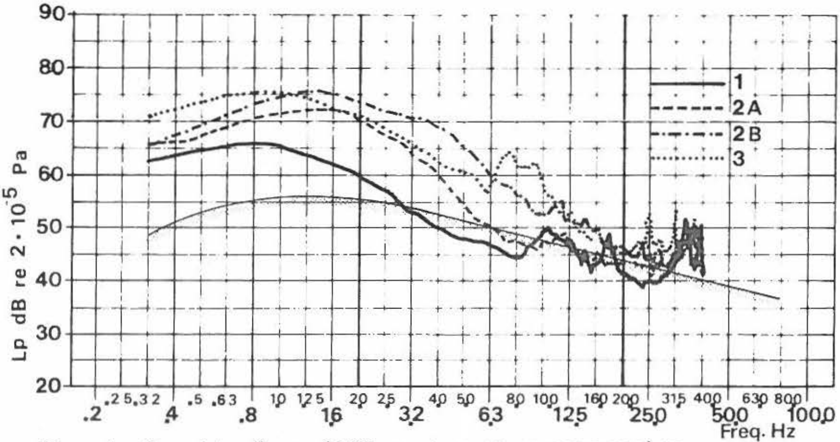


Fig. 4. Results from different system categories.

One might already draw the conclusion that one either should use "old fashion" ventilation systems or the type represented by category 2A. A conclusion of this kind is of course premature and much more statistic material must be added. Furthermore much more work in charting and analysing the ventilation technique must be done. Nevertheless it seems obvious that further work in this direction can give evidence of what properties in ventilation plants are good or bad concerning infrasound and low frequency noise; thus eventually leading to design rules and advise.

Reproducibility of results

In a few cases measurements have been repeated in the same location with an interval of approx.one month. This has given almost identical results in the ventilation on - case, one example shown in the fig. 5 and 6. The background noise (ventilation off) shows considerable variation which in this case could be explained by heavy wind blowing and plenty of people in the building in the case shown in fig. 6.

Identification of infrasound sources

Sofar much work trying to identify special infrasound sources has not been done although some tests have been made by running differnet parts of the systems. Fig. 6 shows that in this case the dominating part of the infrasound is coming from the supply fan for the room in question and that the infrasound generation has not changed with the inevitable change in running conditions for the supply fan when the exhaust fan is turned off.
Other experiments with changes in system characteristics are hopefully a part of a continued study.

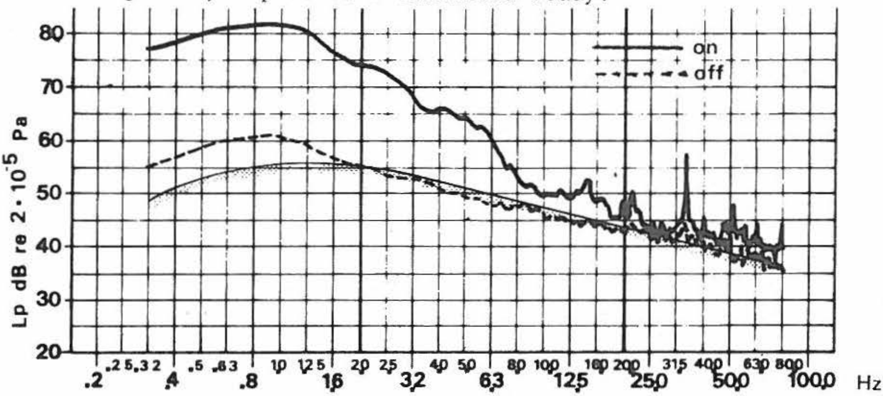


Fig. 5. Infrasound levels in lecture hall 1979-08-02

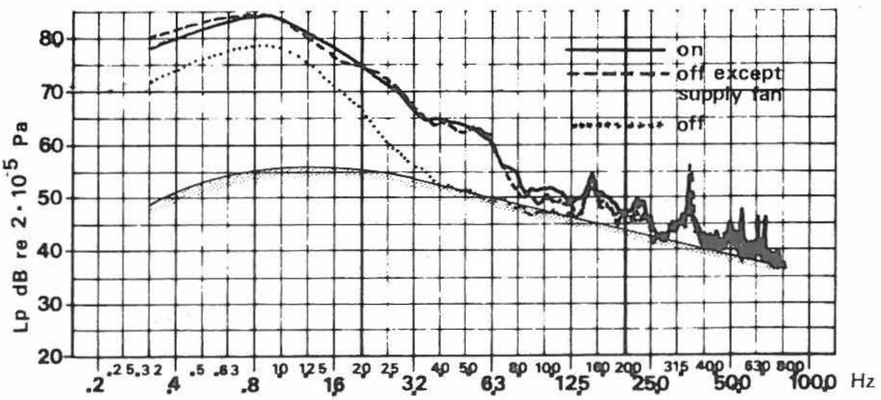


Fig. 6. Same as fig. 5, measured 1979-09-11

Conference on
Low Frequency Noise and Hearing

7–9 May 1980
at Aalborg University Centre
Aalborg, Denmark
Proceedings edited by
Henrik Møller and Per Rubak

Vibration Problems due to Low Frequency Noises from an Electric Power Station

Niichi Nishiwaki, Takuji Mori and Noboru Fujio
Nishiwaki Laboratory, Noguchi Institute, 1-8-1, Kaga, Itabashi-ku, Tokyo, Japan

Summary : Chattering noise problems of glass windows of residential houses, near an electric power station, occur. By utilizing a noise source detector, it was found that low frequency atmospheric vibration of 16 and 20 Hz came from an inlet port of forced draft fans of main boilers. Specially designed silencers of low frequency type were equipped and considerable decreases of SPL of 16 and 20 Hz were obtained. Other noise source of 9 ~ 10 Hz and of 12.5 Hz are from piping systems of induced draft fans and chambers of desulfurizing equipments for exhaust gases from boilers. Special silencing methods are now under preparation.

1. Chattering noise problems of glass windows of houses.

There happened chattering noise problems of windows of residential houses, near an electric power station. These houses are located about 680 m from that station. (Fig.1) There are low frequency noises of about 55 dB(Lin.) at 20 Hz, of about 53 dB at 16 Hz, of about 63 dB at 9 ~ 10 Hz and of about 65 dB at 12.5 Hz. (Fig.2)

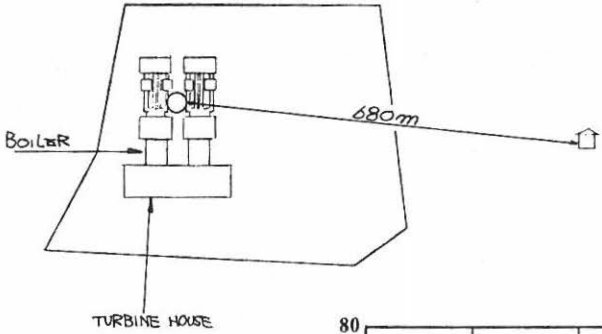


Fig.1

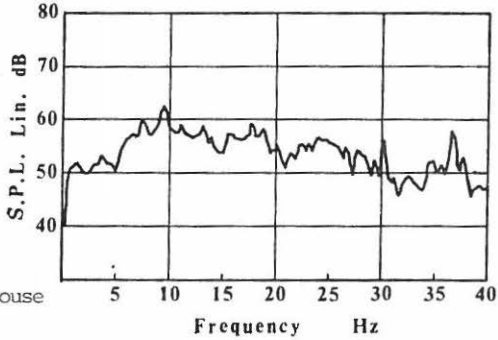


Fig.2
at a residential house

2. Detection of noise sources.

By utilizing a detector for noise sources, we found that forced draft fans (FDF) for boilers were emitting noises of 16 and 20 Hz. (Fig.3 and Fig.4) And also it was found that piping systems for induced draft fans for boilers were emitting low frequency noises of about 90 dB at 9 $\sim$ 10 Hz and of about 87 dB at 12.5 Hz. (Fig.5 and Fig.6)

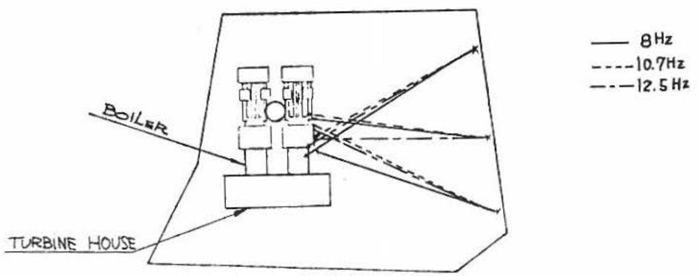


Fig.3

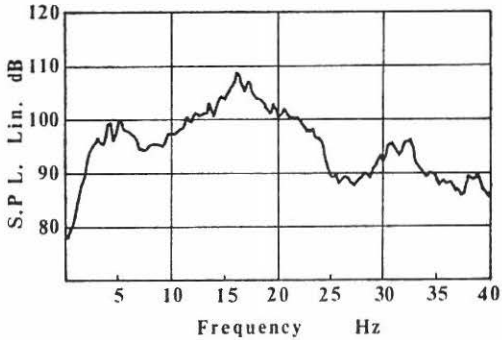


Fig. 4 at a 1 m point of an inlet of a FDF

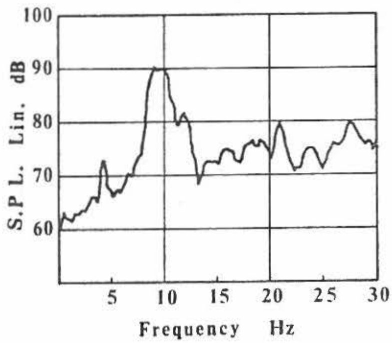


Fig. 5 at a cooling chamber

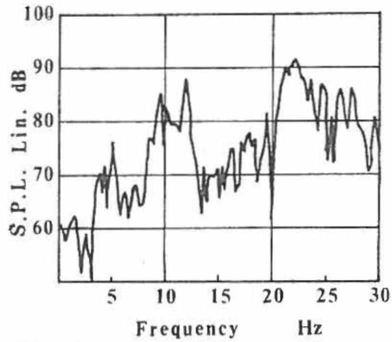


Fig. 6 at a piping near an induced draft fan

3. Silencers of low frequency type for forced draft fans.

3-1. Silencers of reactive type were designed.

Following conditions were adopted.

1) Decreases of S.P.L. is about 10 dB at 16 $\sim$ 20 Hz.
2) S.P.L. of audible range must be less than 90 dB(A) at a 1 m point from inlet ports.
3) Pressure loss of silencers must be less than 40 mmAq at flow rates of 11500 m^3/min.

3-2. Model tests for a silencer of low frequency type

Fig.7 shows system diagram of a forced draft fan and a silencer of reactive type. A model silencer of 1/10 size was prepared.

A speaker, placed at a place of FDF, emitted noise. Fig. 8 shows insertion loss dB of the model silencer. Dotted marks are obtained by speaker tests and full lines are from theoretical calculations.

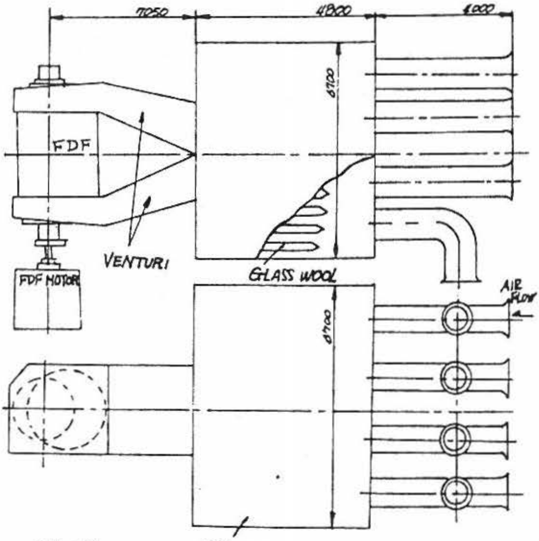


Fig.7

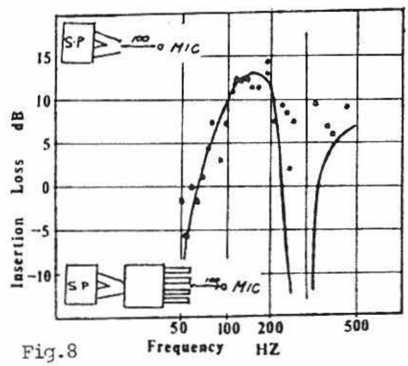


Fig.8

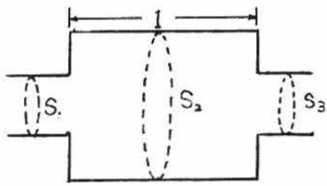


Fig. 9a

3-3. Theoretical calculation

An equation for transmission loss (T.L.)of a reactive type silencer (Fig.9a) is

$$\text{T.L.} = 10\ \log_{10}\left\{1 + \frac{1}{4}\ (m - \frac{1}{m})^2\ \sin^2 Kl\right\}\quad \text{(dB)} \qquad (1)$$

c = sound velocity f = frequency Hz $K = \frac{2f}{c}$

l = length of a reactive silencer $m = \frac{S_2}{S_1}$

For a case shown in Fig.9b.
Equation for insertion loss (I.L.) is as follows

$$\text{I.L.} = 10\log\frac{1}{m_{30}}\left|\frac{m_{10}}{1-R_0e^{-2ikl_0}}\left\{i(1+R_3e^{-2ikl_3})\ (\sin kl_1\cdot\cos kl_2 + m_{21}\cos kl_1\cdot\sin kl_2) + m_{32}(1-R_3e^{-2ikl_3})\ (m_{21}\cos kl_1\cdot\cos kl_2 - \sin kl_1\cdot\sin kl_2)\right\}\right|^2 \qquad (2)$$

$m_{10}=S_1/S_0$, $m_{21}=S_2/S_1$, $m_{32}=S_3/S_2$, $m_{31}=S_3/S_1$, $m_{30}=S_3/S_0$

R_0, R_3: end reflection rate of pipe l_0, l_3

(1) $R_0=R_3=0$, $S_0=S_1=S_3$

$$\text{I.L.} = 10\log\left|1+(m_{21}^2-1)\,(1-\frac{m_{21}^2+1}{m_{21}^2}\sin^2 kl_1)\sin^2 kl_2 + \frac{1}{2}(m_{21}-\frac{1}{m_{21}})\sin 2kl_1\cdot\sin 2kl_2\right| \qquad (3)$$

(2) $R_0=R_3\doteqdot-1$, $S_0=S_1=S_3$

$$\text{I.L.} = 20\log\left[\frac{\cos kl_1}{\cos kl_0}\left\{\cos kl_2\cdot\cos kl_3 - m_{21}\sin kl_2\cdot\sin kl_3 - \tan kl_1\,(\cos kl_2\cdot\sin kl_3 + \frac{1}{m_{21}}\sin kl_2\cdot\cos kl_3)\right\}\right] \qquad (4)$$

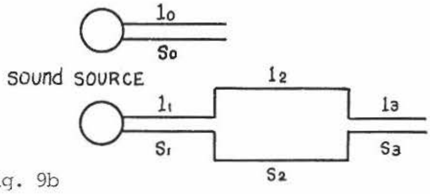


Fig. 9b

3-4. Decrease of S.P.L. of actual silencers

Fig.10 shows a photograph of an actual silencer and Fig.11 shows S.P.L. at a 1 m point from an inlet of the FDF. Noise level of

16 and 20 Hz were decreased by about 7 dB at the residential district. (Fig.12)

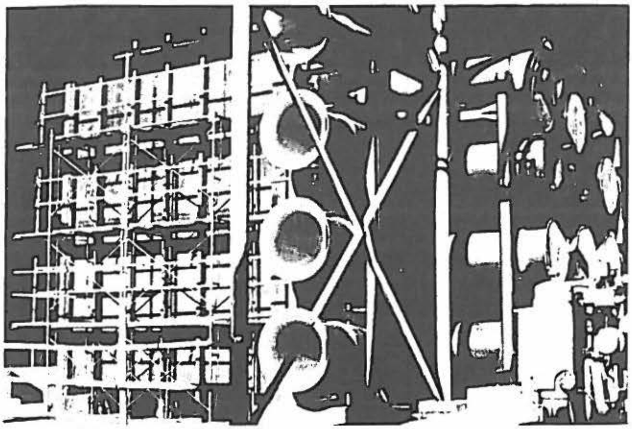


Fig. 10

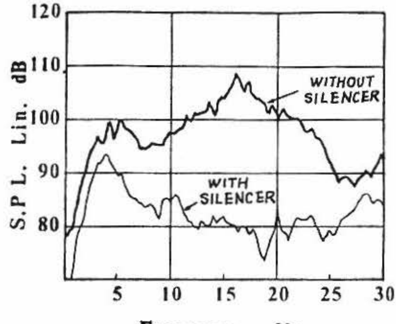


Fig.11

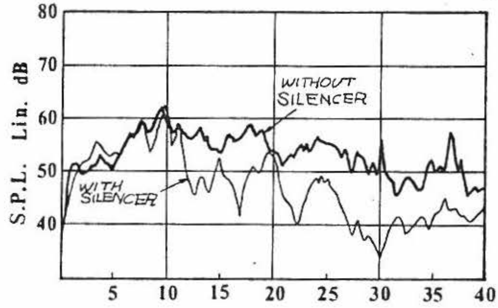


Fig. 12

4. Model tests of 1/20 size for the piping system of induced draft fans.

Model tests of 1/20 size for the piping system of induced draft fans were also proceeded and showed that there were surging phenomena between the induced draft fan and the cooling chamber, having noises of about 200 Hz. A model silencer was equipped with this model system and results of the model test showed that noise level of 200 Hz was decreased by about 6 dB. (Fig.13) We are now preparing special silencers for piping systems of the induced draft fans and noise level of 9 ~ 10, 12.5 Hz are expected to be decreased by about 2 ~ 3 dB at the residential district.

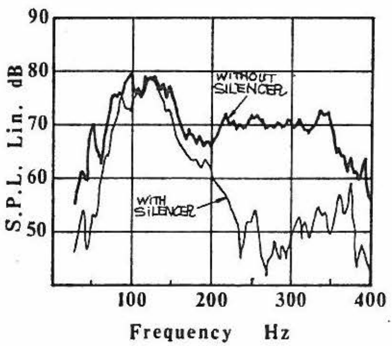


Fig. 13

5. Acknowledgement.

The author would like to thank many people who assisted us to measure noises and also Mr. M. Yashiro, Mr. S. Motojima and other who helped us to do model tests.

Many cooperative works given by Dr. Teruo Obata are gratefully acknowledged.

Conference on
Low Frequency Noise
and Hearing

7–9 May 1980
at Aalborg University Centre
Aalborg, Denmark
Proceedings edited by
Henrik Møller and Per Rubak

Low Frequency Noise in Buildings

Gerhard Volberg, Müller-BBM GmbH Schalltechnisches
Beratungsbüro, Robert-Koch-Str. 11, 8033 Planegg b. München

1. Introduction

In recent years, there is an increasing number of complaints from residents adjacent to railway and road traffic tunnels. In addition, complaints were registered from surface routes about annoying vibrations.

In Germany, two standards deal with the rating of vibrations: DIN 4150 [1] and VDI 2057 (draft) [2]. The permissible values given in the VDI guideline are adapted to those of ISO 2631 [3], whereas the maximum values recommended in DIN are low. In the following, the lower values of DIN 4150 will be discussed exclusively.

The rating curves KB of the DIN standard are shown in fig.1. The heavy line for KB = 0,2 is applicable to residential areas (rated exclusively and generally residential).

The rating curves are based on experimental findings. Test persons had been exposed to sinusoidal stimuli which had to be compared to a reference signal (usually 20 Hz). This procedure may not be suitable for the assessment of non-sinusoidal transient vibrations. Experiments have shown that such transients may cause annoyance inspite of being below the sensitivity limit corresponding to DIN 4150 [4,5,6] . Consequently, the vibration rating criteria of both German and international standards are not adequate for the assessment of structure borne noise from road and rail traffic. But there is experimental evidence that quality of living is not impaired by vibration, but by secondary low frequency sound radiated from ceiling and walls [7, 8].

In the following, a couple of calculated and measured examples are presented together with rating procedure. There is not enough knowledge for the rating of very low frequency sound.Thus, the frequency range will be limited to a lower end of about 20 to 30 Hz. This limit is sufficient for vibrations transmitted from road and rail traffic into buildings. A typical spectral distribution (one-third octave band velocity level) of vibrations measured at the foundation of a building while a rapid-transit train passed through a tunnel 20 m away is shown in fig. 2. The maximum can be observed in the 40 Hz band. Depending on train velocity and tunnel shape,maxima may be shifted to higher or lower frequencies, but will allways stay in the range from 30 to 100 Hz.

2. Calculation of sound from vibrations

Vibrations, exciting a room's wall of surface area S and radiation efficiency σ at a velocity level L_v result in a sound pressure level L_p in this room that depends on the room absorption A as follows:

$$L_p = L_v + 10 \lg \sigma - 10 \lg \frac{A}{4S} \qquad (1)$$

For example, the rating number KB = 0,2 recommended in DIN 4150 results in a velocity level (re 5×10^{-8} m/s) of 72 dB (i.e., 0,2 mm/s) at 50 Hz. A typical room of 5 x 3 m floor area, 3 m height and 1 sec reverberation time has a room absorption A of 7 m². Assuming radiation from all walls and the ceiling at an efficiency $\sigma = 1$, a sound pressure level of 88 dB or 58 dB(A) is calculated which already exceeds permissible outdoor sound pressure levels in residential areas (see TALärm) [9] .

A simplified formula for the A-weighted pressure level may be used for living and bedrooms only:

$$L_{pA} = L_{v,63} - 15 \text{ dB(A)} \qquad (2)$$

where $L_{v,63}$ is the velocity level in the octave band centered. Three examples for satisfactory agreement between measured and calculated data are shown in fig. 3 and 4. Particularly, results shown in fig. 4 demonstrate that the sound pressure level indoors is rather high although the feeling threshold for vibrations is not reached. Behold the sound is not transmitted through the windows, but via ground, ceiling and wall vibrations.

The relation between sound and vibration shown in the above examples may be used for environmental protection of buildings close to tunnels [7] . Using measured ground velocity levels, low frequency airborne sound in building can be estimated and protective means can be taken in early stages of planning.

3. Proposal for assessment

As a result of the investigation described it is obvious that rating numbers given in vibration standards cannot be used for the assessment of low frequency sound radiated from vibrating structures. However, rating numbers are needed for such traff.c sound.

Most German standards and regulations concerning the assessment of airborne sound are limited either to energy mean (i.e. equivalent) level (DIN 18005) [10] or to non-traffic sound (TALärm, DIN 4109) [9,11] .

Only VDI 2719 [12] is applicable to maximum permissible sound in living areas, and also refers to the statistical peak level L_1 which is exceeded in 1 percent of the time on average. Unfortunately, this technical guideline is limited to frequencies above 125 Hz.

Based on subjective experience, gained from measurements, and on few inquiries, it is proposed to extend the guideline data to low frequencies down to approximately 30 Hz. A sudden rise of transients in few third-octave bands requires additional consideration. It is proposed to use a statistical peak level L_1.

In accordance with VDI 2719, the following rating levels are proposed for both living and bedrooms:

Equivalent level	L_{AFm}	=	30	dB(A)
Statistical peak level	L_1	=	40	dB(A).

L_1 is relevant if it exceeds L_{AFm} by more than 10 dB.

The data are proposed for the frequency range above 30 Hz. At lower frequencies other rating scales may be necessary as demonstrated by the following example. Levels up to 78 dB(A) have been measured in a subway control room, caused by street cars passing above. While such A-weighted levels are acceptable in working areas, the corresponding linear sound level at 10 Hz amounted to 120 dB. This may be hazardous to health according to corresponding investigations [13] .

[1] DIN 4150, Part 2 "Vibrations in building - Impact on man in buildings"

[2] VDI 2057 (draft) "Assessment of the impact of mechanical vibrations on man"

[3] ISO 2631 "Guide of evaluation of human exposure to whole body vibrations"

[4] Stüber, C., Hauck, G., Willenbrink, L.:"Körperschall Und Luftschallmessungen an unterirdischen Schienenbahnen"
Eisenbahntechnische Rundschau 21 (1972) 289-300

[5] Martin, D.: "Low frequency traffic noise and building vibration"
TRRL Supl. Report 429 (1978)

[6] Dawn, T., Stanworth, C.: Ground vibration from passing trains"
Journal of Sound and Vibration, Vol.66, No.3 (1979)355

[7] Koch, H.: "Propagation of vibration and structure bound sound caused by trains running at a maximum speed of 250 km/h"
Journal of Sound and Vibration, Vol.51, No.3 (1977)441

[8] Volberg, G.: "Vorschläge zur Beurteilung von Immissionen durch U-Bahn-Verkehr
VDI Bericht 284 (1977) 33

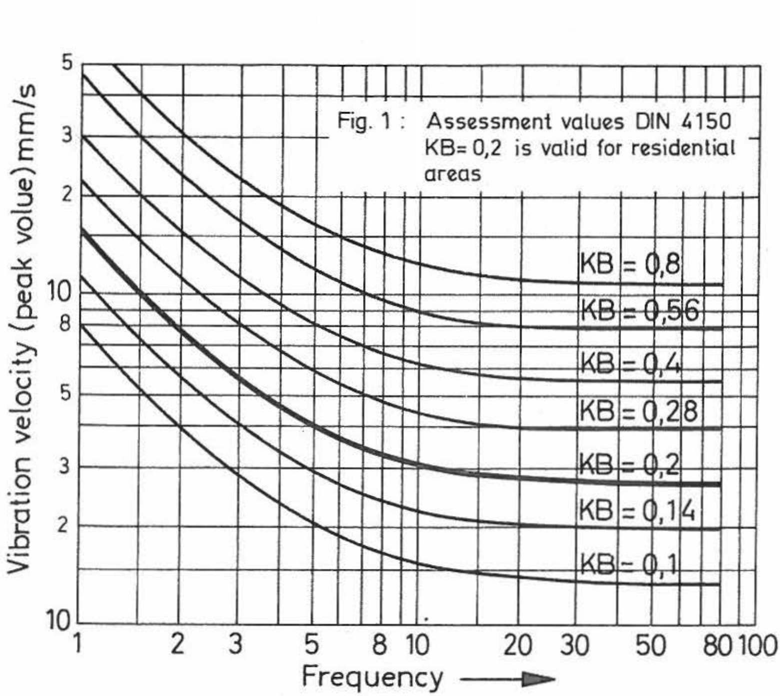
[9] Technische Anleitung zum Schutz gegen Lärm (TA-Lärm) (1968)

[10] DIN 18005 "Noise abatement in town planning" (1971)

[11] DIN 4109 "Noise control in buildings" (1962)

[12] VDI 2719 "Sound insulation by windows" (1973)

[13] Gono, F.: "Infraschall und seine Wirkung auf den Menschen"
Arbeitsmedizin, Sozialmedizin Präventivmedizin
Juli 1978



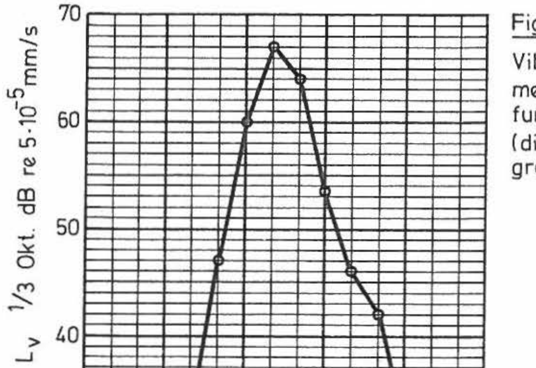


Fig. 2

Vibration velocity level measured on a building fundament (distance to the underground train tunnel 20 m)

Fig. 3: Vibration velocity level spektrum in buildings near by a subway tunnel

① First floor : measured: ~33 dB(A), calculated: 35 dB(A)

② Ground floor : measured: 41 dB(A), calculated: 39 dB(A)

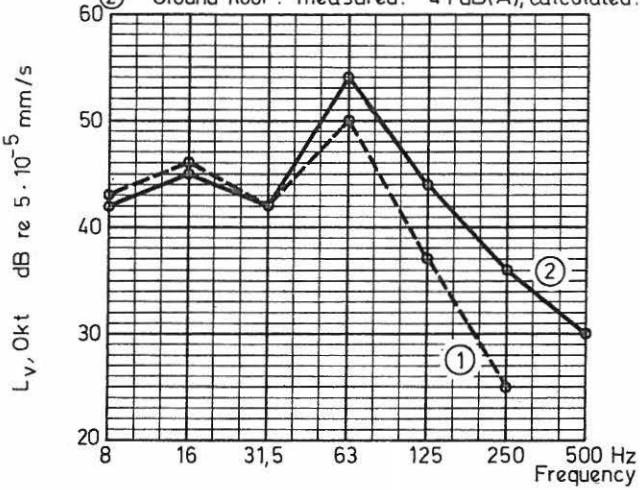
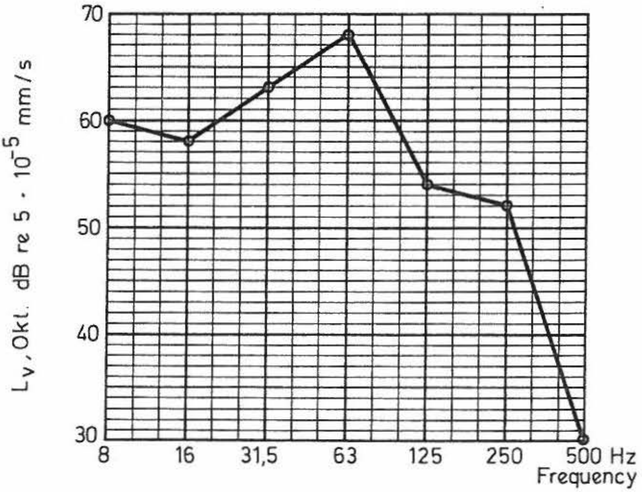


Fig. 4 : Vibration velocity level spektrum in a building near by a subway track, measuring point: vertikal vibration on the floor

measured: 52 dB(A) calculated: 53 dB(A)



Conference on
Low Frequency Noise and Hearing

7–9 May 1980
at Aalborg University Centre
Aalborg, Denmark
Proceedings edited by
Henrik Møller and Per Rubak

Low frequency noise pollution problems in Japan

Yasuo TOKITA
Kobayasi Institute of Physical Research
(3-20-41.Higashimotomachi, Kokubunji Tokyo 185 Japan)

Introduction

In Japan, noise and ground vibration regulation laws have been established, but there is no regulation for the low frequency noise or infrasound. Recently complaints from residents against low frequency noise pollutions nearby factories, airport, highway long bridge, dam and so on are becomming rather great amount. Complaints are sometimes related with the window and door rattling and unpleasant feelings at the comparatively lower sound pressure level region.

The Government (Environment Agency) has been starting the surveys about the low frequency noise pollution, since 1976. The questionnaire investigation and acoustic measurements were carried out in 1976 in the surrounding areas where complaints had been received, and continnually low frequency noise effects on the fittings of houses, man and animal response and reduction techniqes have been studied.

$.1 Complaints of low frequency noise

Fig. 1 shows the transition of complaint's numbers from inhabitants due to low frequency noise or infrasound which accepted at local government in Japan.

The main complaints are due to factorie's machine; big sized blower, reciprocating machine (compressor and pump), furnace, aircraft; take off, landing and engine mentenance, highway long bridge, dam discharge, high speed rail way running into tunnel, and sometimes small sized air conditionning apparatus using in private home.

The categories of complaints are as follows,

1) Structural complaints
   * Shaking motion and rattling of window and door.
   * Mechanical damage (but not yet clarify the correlation between damage and sound pressure)
2) Psychological complaints
   * Disturbance of sleep and rest.
   * Irritation.
   * Disturbance of study and reading.
3) Physiological complaints
   * Headache.
   * Tinnitus.
   * Oppressive sensation & etc.

Fig. 2-4 indicate the relation between complaints and sound pressure level of which frequency range is 2-90 Hz. This survey had done arround the places where complaints had occured.

As it is clear from these figures mentioned,

1) Complaint occures at even low sound pressure level; about 65 dB.
2) Even though at high sound pressure level, sometimes there are no complaints.

It will be seen that the complaints are due to individual feeling, then the level difference among persons is very large, but 75 dB would be the critical sound pressure level as the occurrence of complaint.

$.2 Generating sources and propagation patterns

Fig.5-8 are the examples of the propagation patterns of low frequency noise.

Fig.5 is the case of that generating source is the furnese of cupola. The generating mechanisms would be the oscilating burning in the furnase and resonance inside of the chimuny. The dominant 1/3 octave frequency bands are 40 and 10 Hz.

Fig.6 is the case of tunnel. According to inrush of the high speed train(Shinkansen: speed is about 200 Km/h) at the opposit side of long tunnel(about 3 Km length), the large sound pressure as similar to explosion generates from the another open side, and dominant frequency is 10 Hz, but having rather wide band component.

In the case of Fig.5 and 6, it would be consider that the generating source may be a point source.

Fig.7 is the case of highway long bridge. Low frequency noise due to running over expansion joint has a figures with dominant frequencies, 3.15, 16 and 31.5 Hz. The lowest frequency depend on the fundamental long span vibration of bridge, middle frequency depend on the higher modes of bridge, and highest frequency depend on the short span vibration of bridge. In this case, propagation pattern is as similar to line source generater.

Fig 8 is the case of dam discharge. Dam discharge generates large low frequency sound pressure not only in the case of overflow type dam but also arch type dam, as similar to waterfall. In this case, the dominant frequencies are containning 4 to 8 Hz, and it would be consider that the generating source is falling pond surface, and then it would be wide spreaded surface.

$.3 Government approach to attack low frequency noise pollution

The Environment Agency has been conducting research and study on low frequency noise pollution to decrease the low frequency noise complaints as follows.

1) Complaints survey with questionnaire and acoustic measurement.
2) Structural response of window etc. due to low frequency sound pressure.
3) Psychological and physiological effect of low frequency noise on man in the region of rather lower levels.
4) Survey on low frequency noise generation mechanisms and reduction techniques.
5) Survey on low frequency noise in natural environment and residence.
6) Measuring apparatus of low frequency noise to evaluate low frequency noise pollution.
7) Procedure of regulation.

$.4 Conclusion

In Japan, low frequency noise complaints had occured in the region of rather low sound pressure level. On the other hand, in another country, the survey and research had started in higher sound pressure level. Then the goal of each may be different in Japan and other country, but people wishes to have a nice environment. Then as long as one's hope, we would make a effort to reach the goal "Nice Environment", on the basis of technical research.

Reference

Survey report of Environment Agency(Japan) about infrasound and low frequency noise. 1977,1978,1979.

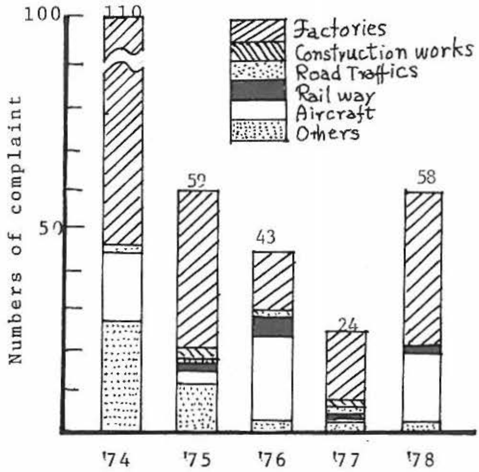


Fig.1 Transition of complaints from 1974 to 1978, in Japan. (Environment Agency)

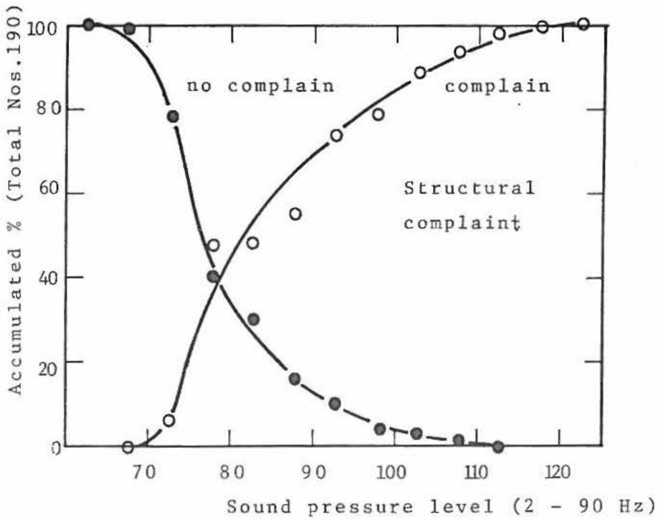


Fig.2. The relation between mechanical complaint and sound pressure level.

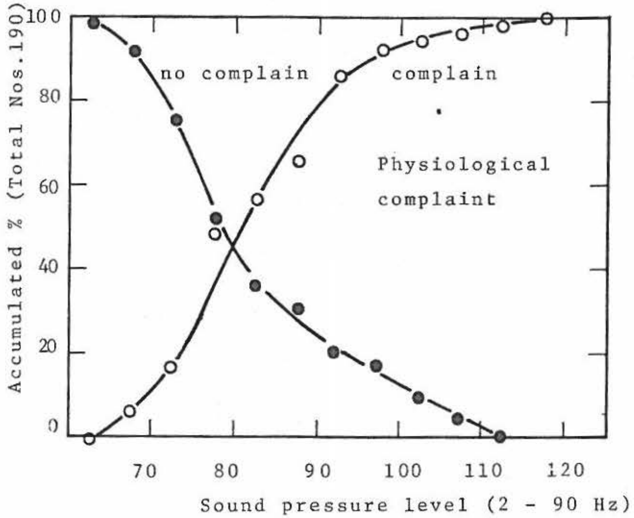


Fig.3. The relation between physiological complaint and sound pressure level.

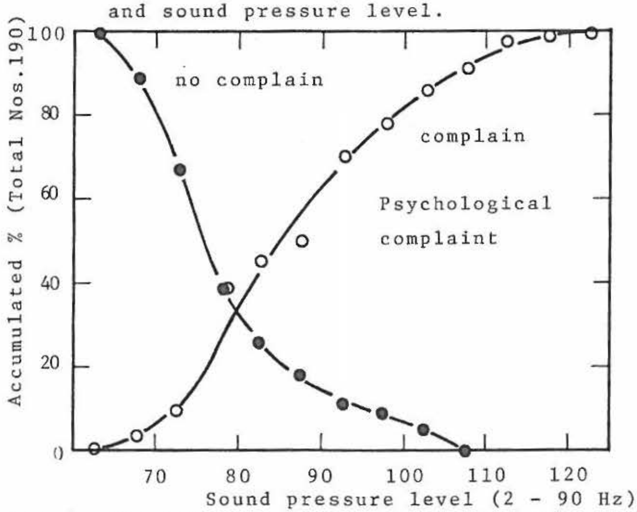


Fig.4. The relation between psychological complaint and sound pressure level.

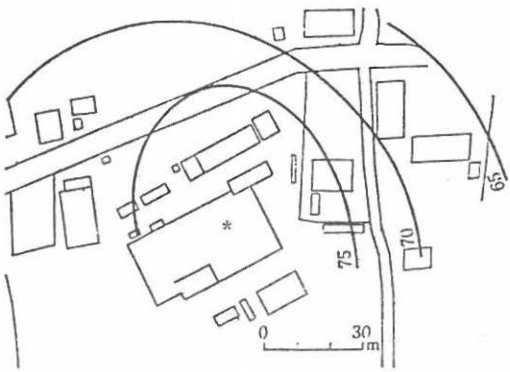


Fig.5 Example of propagation pattern in the case of factory. (source; cupola)

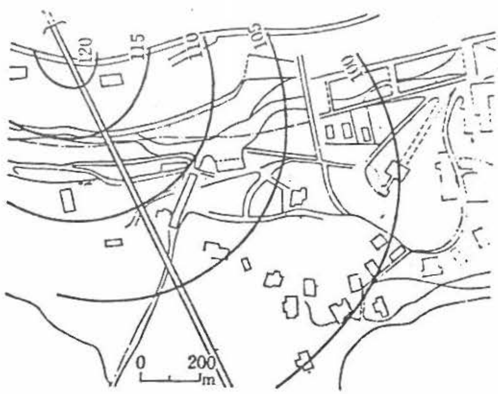


Fig.6 Example of propagation pattern in the case of tunnel.

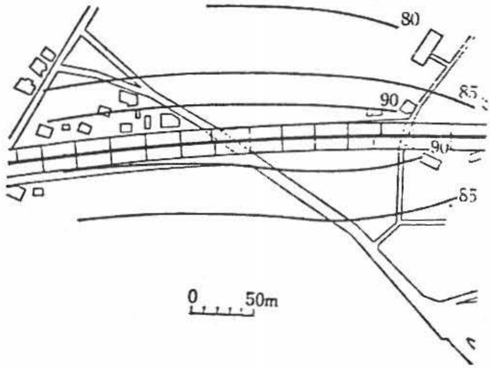


Fig.7. Example of propagation pattern in the case of highway long bridge.

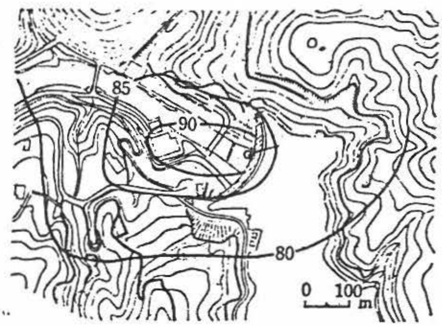


Fig.8. Example of propagation pattern in the case of dam discharge.

Conference on
Low Frequency Noise
and Hearing

7–9 May 1980
at Aalborg University Centre
Aalborg, Denmark
Proceedings edited by
Henrik Møller and Per Rubak

METHODS AND RESULTS OF MEASUREMENTS OF INFRA-NOISE IN INDUSTRY

Danuta Augustyńska

Central Institute of Labour Protection, 1, Tamka str.,
00-349 Warsaw

The paper describes the results and gives the conclusions from measurements of infrasounds generated by low-speed piston compressors. The measurements have shown that these compressors generate infrasounds in acoustic sound pressure levels fluctuating within 100-130 dB at 9-20 Hz frequency range. In some cases, these levels exceed the assumed initial criterion values.

As can be seen from the analysis of studies reported in the literature and studies accomplished in our laboratory, a lot of machines and devices commonly used in industry /for ex. low-speed compressors, especially piston compressors, Diesel engines, industrial fans, blast-furnance blowers, etc./ are sources of infra-noise, the spectrum of that is concentradted at the 0-20 Hz frequency range as well as the range of low audio frequencies. The Acoustics Department of the Central Institute of Labour Protection initiated investigations aiming at the recognition of risks caused by infrasounds in the working environment, methods for their measurements, their assessment criteria and the methods for restricting these risks. At the first stage of the investigations a preliminary injury criterion was elaborated. In the audio frequencies range, this is the curve N 80. In the infrasound frequencies range /2-20 Hz/ according to swedish propositions the 110 dB level was applied. Research for more precised criterion are continued with cooperation to Medical Academy /7/. Further the direct and indirect methods of analysis of infra-noise in industry, using analogue and digital measuring B & K sets was developed. Measurements of infra-noise generated by the most commonly used in Poland low speed piston compressors was performed according to these methods. /See table and fig.1/. The results of the measurements showed that piston compressors are sources of infrasounds of high sound pressure levels fluctuating within the limits of 100-130 dB in the 9-20 Hz frequency range. In some cases, these levels exceed the preliminarly adopted criterion values. One can expect that the use of suitable noise mufflers in the intake systems of the compressors shall radically improve the situation in the fiels of attenuation of the infra-noise by these compressors. /See fig.2/. The works decsribed above are continued.

No	Compressor type	Microphone position	Acoustical pressure level in dB/Lin/	in dB/max. val.2-20Hz/	f_o /in Hz/
1	2	3	4	5	6
1	L-20 /n = 583 rpm/	work-place	100-103	102	19,5
2	- " -	under the air-scoop	110-119	119	19,5
3	L-33 /n = 485 rpm/	work-place	97	97	16,2
4	- " -	under the air-scoop	114	102-112	16,2
5	L-100 /n = 300 rpm/	work-place	108-123	105-122	10
6	- " -	under the air-scoop	130-133	122-132	10
7	300-2K /n = 333 rpm/	work-place	110-113	104-108	11
8	- " -	under the air-scoop	114	105-109	11
9	WS-100 /n = 1000 rpm/	work-place	97-100	98	33,2
10	- " -	at the air-scoop	100-111	111	33,2
11	DR-40 /n = 280 rpm/	at the air-scoop	117	116	9,4

References

1. Augustyńska D.: Results of measurements of infrasounds emitted by piston compressors. The International Conference on Noise Control Engineering, Inter-noise 79, Warszawa - Poland, September 11-13, 1979.
2. Augustyńska D.: Méthode, critères, évaluation et résultats des mesures du bruit infrasonore. Internationales Symposium "Schutz der Arbeiter vor Lärm", Dresden, 27-30.11.1979.
3. Bogusz B., Renowski J.: Infrasounds. Prace naukowe Instytutu Telekomunikacji i Akustyki Politechniki Wrocławskiej, No 39, 19, 1979.
4. Broner N.: The effects of low frequency noise on people - a review. Journal of Sound and Vibration. Vol. 58. No 4, 1978.
5. Brüel P.V.: Limits for infrasound and ultrasound in factories. The International Conference on Noise Control Engineering, Inter-noise 79, Warszawa - Poland, September 11-13, 1979.
6. Gono F.: Infraschall und seine Wirkung auf den Menschen. Arbeitsmedizin, Sozialmedizin, Präventivmedizin, No 7, 1978.
7. Szelenberger W., Augustyńska D.: A cabin for investigating the influence of infrasound on man. The XXVI-the Open Seminar on Acoustic, Wrocław - Oleśnica - Poland, 1979.

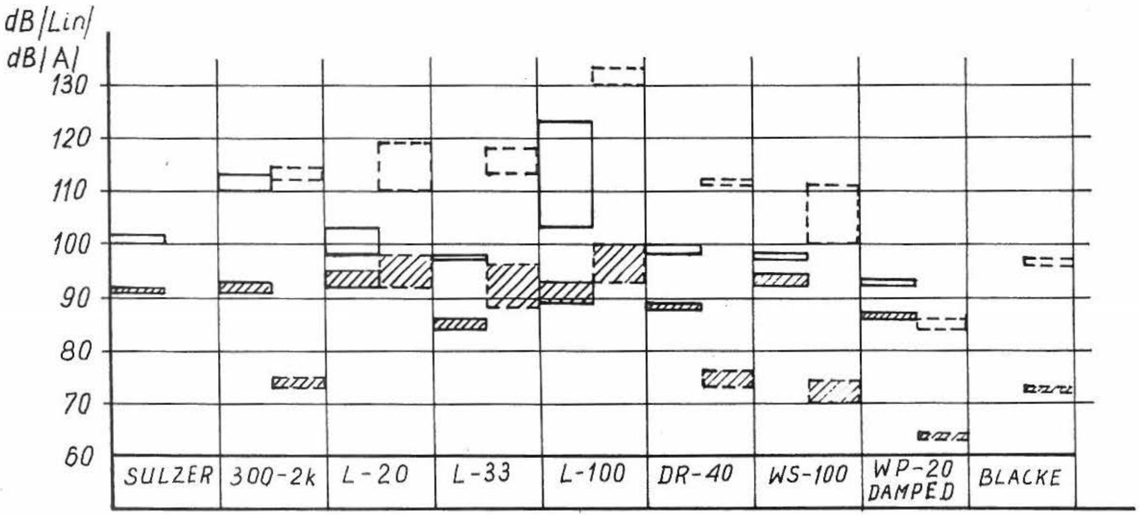


Fig. 1. Sound pressure levels and sound levels A of piston compressors infra-noise measures: a/ at work-place /—/, b/ at air scoop /– –/

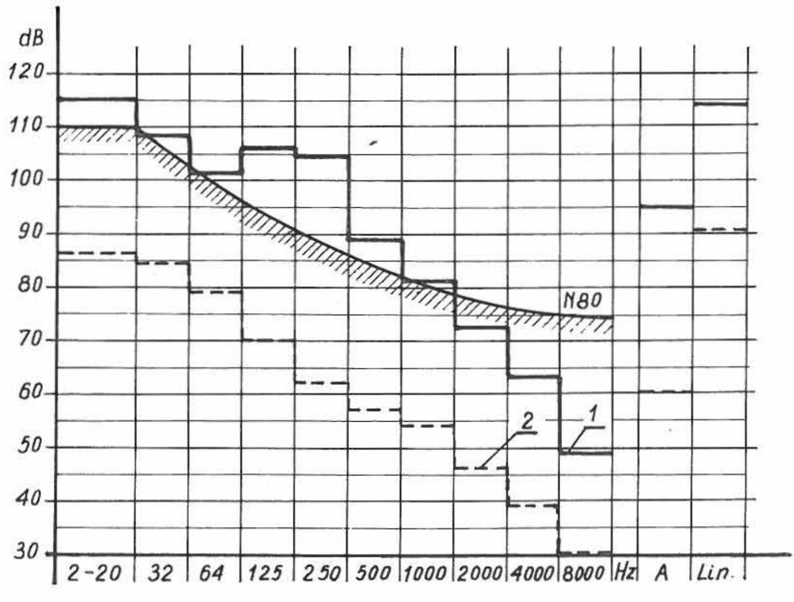


Fig. 2. L-20 compressor infra-noise spectrum measured outside the building:

1 - without silencer in the intake system

2 - with silencer

Conference on
Low Frequency Noise and Hearing

7–9 May 1980
at Aalborg University Centre
Aalborg, Denmark
Proceedings edited by
Henrik Møller and Per Rubak

LOW FREQUENCY CALIBRATION OF MEASUREMENT MICROPHONES

Erling Frederiksen
Brüel & Kjær
Nærum Hovedgade 18,
2850 Nærum,
Denmark.

Condenser microphones are used for practically all sound measurements today. Because of their operational principle and mechanical design they are generally considered to have a flat frequency response at lower frequencies, independent of the acoustical measuring conditions. This implies that the necessary calibration may be limited to a point calibration at one single frequency - 250 Hz is often used.

This consideration is, in practice, fully valid for modern measurement microphones down to 10 - 20 Hz; however, for measurements in the infrasound range, a number of parameters must be considered to influence the frequency response of the microphone and the subsequent instruments in the measuring chain. This fact increases the need for practical infrasound calibration methods.

Some parameters influencing the low frequency response

Compared with the slow variations in atmospheric pressure, the amplitude of the dynamic pressure to be measured is generally extremely small. Therefore, to avoid overload, the microphones must have a controlled vent which allows pressure equalization between the two sides of the diaphragm, i.e. between the internal cavity of the microphone and the air in front of the diaphragm. At low frequencies the vent causes a change in the microphone's sensitivity. The pressure equalization time constant should be chosen as a compromise between linearity of frequency response and ability to equalize.

The equalization time constant and the external region to which the equalization takes place are two of the dominant parameters determining the low frequency response. Before starting calibration for a specific measurement purpose, it is very important to know if the opening of the equalization vent is or is not facing the sound field in the measurement situation. The frequency response of the same microphone is completely different for the two cases. Examples of the principle of the two different situations is shown in Fig.1 and the corresponding frequency responses in Fig.2 (A1 and B1). The calibration condition must correspond to the actual measurement situation.

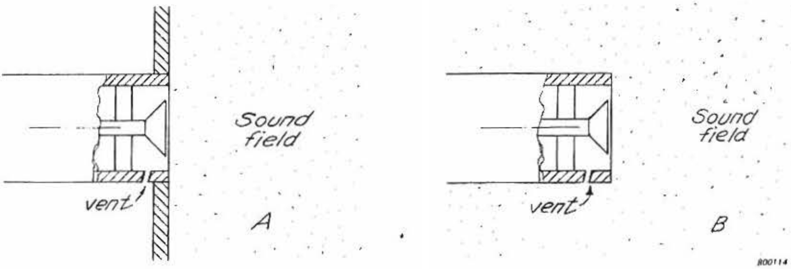


Fig. 1. Equalization vent outside (A) and inside (B) the sound field

For a specific transducer the lower limiting frequency may be altered by changing the resistance of the vent. By closing the vent channel and thus allowing leakage to occur only through stray leakage, a very low cut-off frequency is obtained; Fig.2 (A2 and B2) shows the two resulting responses.

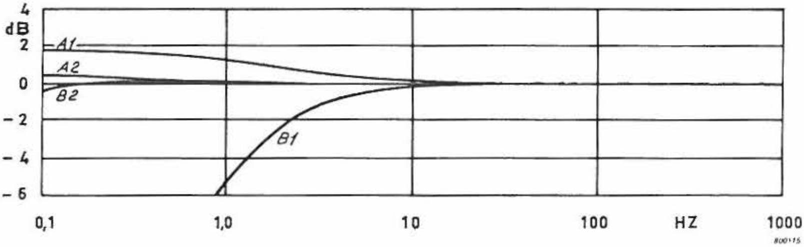


Fig.2. Frequency responses of 1" microphone. Vent outside (A1 and A2) and inside (B1 and B2) the sound field. Nominal vent resistance (A1 and B1). Partly sealed vent (A2 and B2)

The impedance of the cavity behind the diaphragm also influences the lower limiting frequency. The impedance varies proportionally to the ambient pressure; as most measuring microphones have relatively low air stiffness compared with the stiffness of the diaphragm, the lower limiting frequency varies proportionally to the ambient pressure variations. This fact is of less importance for measurements performed at ground level, but for special applications, such as sound measurements in space craft and aircraft as well as in diving tanks, the effect has to be taken into account. See examples of frequency responses.

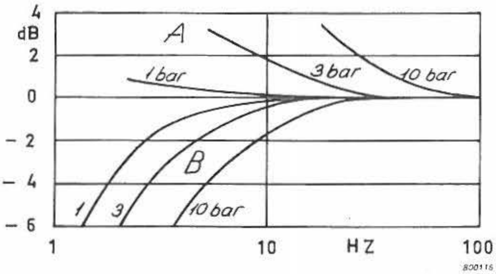


Fig.3. Frequency response of a 1" microphone at various ambient pressures. Vent outside (A) and inside (B) the sound field

A minor effect is due to the air compression process occurring in the cavity, which changes from adiabatic conditions at higher frequencies to isothermal conditions at lower frequencies. The change causes an increasing sensitivity at low frequencies which is most clearly observed with microphones having a relatively high proportion of air stiffness as well as a high equalization time constant, see Fig.4.

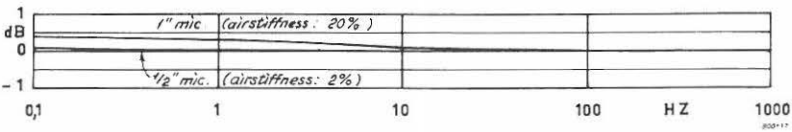


Fig.4. Frequency responses of 1" and 1/2" microphones. The low frequency sensitivity increase is due to the change to an isothermal compression of the air in the internal cavity

A significant parameter is the combination of the microphone and the electronic system being connected. In the case of modern FET-preamplifiers having input impedances of 10 GΩ or more, very low cut-off frequencies are obtainable. If the transducer is shunted with a capacitor, even lower frequencies may be covered by the system, see curves in Fig.5. (In practice this is possible without limiting the lower part of the dynamic range, as sensitivity and noise are reduced equally). To obtain a flat response far below 1 Hz, a carrier frequency system must be used, see examples of frequency responses in Fig.5.

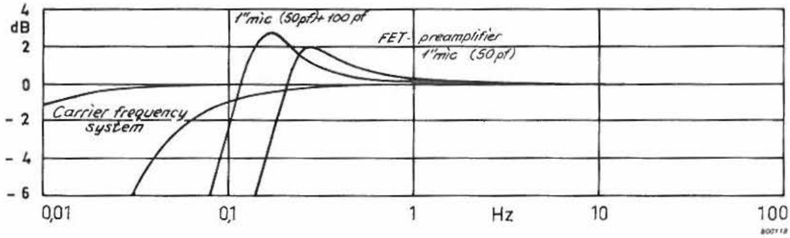


Fig.5. Frequency responses of electronic systems valid for two different source impedances (FET - preamplifier) and for two different settings of cut-off frequency (Carrier Frequency System)

As can be seen, several parameters influence the low frequency (infrasound) response of a measuring system. For many applications, the specifications of the elements forming the measurement chain ensure the required measuring accuracy, but in cases where the environment differs significantly from normal conditions, and in cases where the system is going to be used to its very limits, a calibration which takes the actual measurement situation into account is necessary.

Calibration Methods

Different methods are available for calibration of infrasound measurement systems, some of which take only the response of the electrical system into account, while other methods allow calibration of the complete system, including the mechanical and acoustical parameters.

In some cases where well-defined acoustical transducers are used, the less complicated electrical calibration may be sufficient. Two methods, useable in connection with DC-polarized microphone systems and with Carrier Frequency Systems respectively, should be mentioned briefly.

Insert Voltage Calibration Technique

This method is used for determining the amplification of a preamplifier with a specific microphone cartridge as a source when Laboratory Standard Microphones are being calibrated. (It is described in ANSI and IEC-recommendations). Furthermore, the method is convenient for testing the frequency response of a system using the actual microphone impedance as source impedance. The principle is shown in Fig.6. The housing of the microphone cartridge, being the ground terminal of the source, is separated from the ground terminal of the preamplifier which allows series connection of an electrical source; the signal from that substitutes the open circuit signal delivered from the microphone when a sound pressure is present. The frequency responses of the FET - preamplifier shown in Fig.5 are obtained by use of this technique.

Additionally, the principle is practical for recording reference signals on tapes during the actual measurement situation.

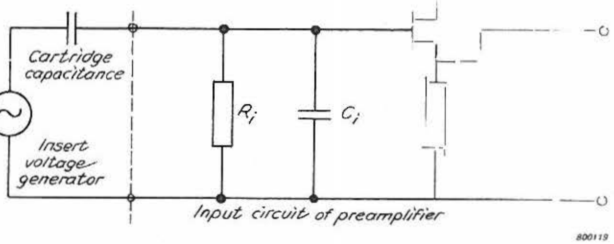


Fig.6. Principle of Insert Voltage Calibration

Electrical calibration of Carrier Frequency Systems

Carrier systems do not respond directly to analog electrical signals. The signals have to be transformed to capacitance variations. Fig.7 shows a simple circuit which solves this problem. Variations in the DC - voltage across the so-called capacitance diode make its capacitance change. The series capacitance seen from the carrier system of the diode and the capacitors must correspond to the capacitance of the cartridge which is going to be used. The system shown can be used for frequency response calibration up to 100 Hz (determined by the RC time constant) but is not recommended for absolute calibration. See responses of a carrier system in Fig.5, they are obtained by use of this method.

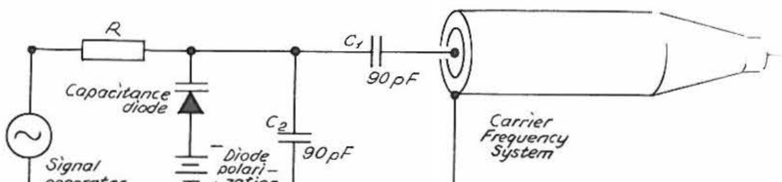


Fig.7. Circuit producing capacitance variations for frequency response calibration of Carrier Frequency Systems

To calibrate the complete measurement system and thus to include the mechanical and acoustical parameters, other methods have to be used.

Electrostatic Actuator Calibration

Electrostatic actuators are practical tools for frequency response calibration in the case of microphones having a plane, accessible, metal surface diaphragm.

In principle, an actuator is a conducting plate placed in front of, and electrically isolated from, the diaphragm of the microphone in such a way that actuator and diaphragm form an electrical plate capacitor. If electrical voltage is applied to the actuator, the field in the gap will cause a force to act on the diaphragm. The force is independent of the frequency, which makes the system very practical for frequency response calibration. However, due to the edge effect of the plate capacitor (actuator), and problems in determining the plate distance precisely, the exact value of the force is difficult to determine. The method is of limited value for absolute calibration as accuracy is of the order 1 - 2 dB. The equivalent sound pressure is given by:

$$p_e = \frac{\epsilon \, E^2 \, (t)}{2d^2}$$

ϵ = absolute dielectric constant for the gas in the plate gap ($\simeq \epsilon_o = 8.85 \cdot 10^{-12}$ F/m)
$E(t)$ = actuator voltage as a function of time
d = effective distance

Proper choice of DC and AC voltage (800 V (DC) - 30 V (AC) - 0,5 mm distance) can give an equivalent sound pressure of approximately 1 Pascal.

It should be noted that no signal is applied to the vent, which reduces the number of application cases for the method, but in cases where the method can be used it offers great advantages, especially for the analysis of microphone behaviour in extreme environments, as the signal generated is practically independent of the ambient conditions. The actuator can be used for calibration in cases where the vent is outside the sound field (Fig.1A) and thus the corresponding curves at Fig.2 - 3 and 4 can be obtained that way.

Pistonphones as low frequency calibrators

As has earlier been described in B & K literature, the usual pistonphone type of calibrators suffer from several drawbacks when used for infrasound applications, and unless a complicated mechanical design is undertaken the use is limited to some single frequencies and high sound pressure levels. Furthermore, the piston(s) act as a Constant Volume Displacement Source, which means that the sound pressure generated is proportional to the impedance of the cavity. This impedance is a function of the volume (and thus of the microphone connected), the ambient pressure, leakage, the gas being compressed, and of the compression process, which in the infrasound range changes from adiabatic conditions to isothermal conditions, causing a change in the SPL, depending on the gas, of 2 - 4 dB.

Thus, the pistonphone is generally not practical for low frequency calibration, therefore other types of acoustical calibrators have been developed.

Constant Pressure Acoustic Calibrator

A Constant Pressure Calibrator is, ideally, an acoustical source producing a sound pressure which is independent of the loading microphone and the environmental conditions. (It is the acoustical equivalent of an electrical constant voltage source which maintains the voltage independently of the current flowing). In practice, such an ideal system can only be realized to a certain degree. The system should have a very low acoustical impedance compared with any actual loading impedances.

A physical realization of a Constant Pressure Calibrator is shown in Fig. 9. Basically, the source is an electrodynamic system coupled to a light weight, large area piston which is mounted with soft springs to obtain the required low acoustical impedance. The desired high load impedance is obtained by minimizing the volume of the couplers used for adapting the microphones being calibrated.

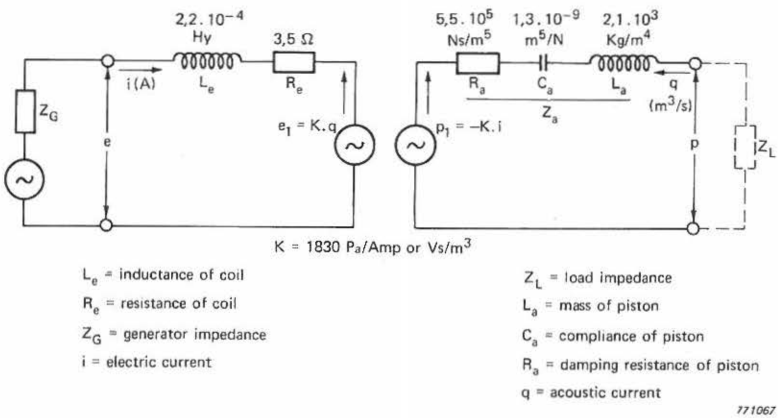


Fig.8. Electrical and acoustical circuit diagram of Constant Pressure Calibrator

The corresponding electrical and acoustical circuit diagram of the system is shown in Fig. 8.

In principle, such a system may operate down to 0 Hz, but in practice is limited by leakage in the couplers. The system shown has a cut-off frequency (–3 dB) of less than 1 mHz at 1 bar. The upper limiting frequency is determined by the mass of the moving system, which at higher frequencies increases the acoustical source impedance. The upper 3 dB limit is at 500 Hz. Two couplers have been designed; one of which applies the sound pressure to the diaphragm only (Fig.1A), while the other one surrounds the whole microphone with the sound pressure (Fig.1B). Using these couplers, the frequency

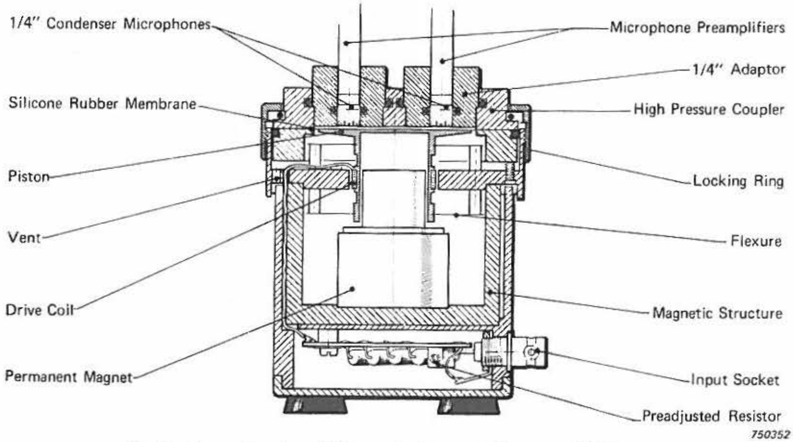


Fig.9. Cross Sectional View of Constant Pressure Calibrator

response is flat within ±2% from 5 mHz to 100 Hz. Practically all low frequency calibrations of condenser microphones and other pressure transducers can be performed using such a system. Figs.2, 3 and 4 illustrate some types of measurement which may be carried out using the Constant Pressure Calibrator described.

A calibrator of this type takes all the parameters of a measuring chain into account, and as it also allows absolute calibration it is a practical tool for many calibration purposes.

Conclusion

Calibration of microphones or measuring systems for use below 20 Hz is often necessary as many parameters may influence the frequency response.

No single method can solve all low frequency calibration problems occurring in the laboratory and in the field. The methods here and other methods may be used as complements to extend the calibration range and to increase the reliability of the results obtained.

Although all the methods of calibration mentioned here may be used in the laboratory, the Insert Voltage Calibration Technique and the Constant Pressure Calibrator are the most practical methods for field use.

Conference on
Low Frequency Noise and Hearing

7–9 May 1980
at Aalborg University Centre
Aalborg, Denmark
Proceedings edited by
Henrik Møller and Per Rubak

A THREE ELEMENT MICROPHONE ARRAY FOR LOCATING SOURCES OF AUDIBLE LOW FREQUENCY NOISE

R.N. Vasudevan and H.G. Leventhall, Chelsea College,
University of London, Pulton Place, London, SW6 5PR.

Summary A three element microphone array for locating the source of environmental low frequency noise in the frequency range 30-150 Hz is described. The instrument employs an equilateral triangular layout, matched amplifiers, high 'Q' filters and phasemeters. The system is shown to function satisfactorily for both pure tone and narrow band noise.

***

Over the past few years, environmental low frequency noise in the range 20-200 Hz has caused considerable disturbance and annoyance. The evidence so far available, suggests that the subjectively unpleasant phenomenon is due either to low frequency tone components or spectra of an unbalanced shape, devoid of specific tone components. (Vasudevan and Leventhall, 1979; Vasudevan and Gordon, 1977).

Detection of the source of low frequency sounds is often difficult due to lack of directional cues and the low intensity level of many such sounds. This paper describes an instrument designed to locate the source, especially where the presence of tone components has been established by earlier field measurements.

Instrumentation

Theory: Detection of the source of low frequency noise is carried out by the use of a three element microphone array. Barber (1963) has shown that such a system is at its optimum when the wavelength is twice the length of the sides. Further, for the kind of 'all round' looking that is essential for locating a low frequency noise source, the layout of an equilateral triangle is preferred. This geometry was therefore adopted.

From Fig. 1, for a plane wavefront arriving at an angle Θ, the path difference 'd' between two microphones M_1 and M_2 is $d = l \sin (30-\Theta)$. The corresponding difference in phase between the signals induced at M_1 and M_2 is $\emptyset_{12} = 2\pi l \sin (30-\Theta)/\lambda$, where λ is the anticipated wavelength. Since the sides of the triangle are set at half the anticipated wavelength, the phase difference can be written as $\emptyset_{12} = \pi \sin (30-\Theta)$. Similarly, corresponding differences in phase angle $\emptyset_{23}$ and $\emptyset_{31}$, between the other two pairs of microphones can be written as $\emptyset_{23} = \pi \cos (60-\Theta)$, and $\emptyset_{31} = -\pi \cos \Theta$.

As the direction (Θ) of the wavefront changes relative to the base line, for example due to rotation of the array system, the values of $\emptyset$ will vary accordingly and the signals produced by the three pairs of microphones will be alternately in and out of phase. Calculated phase differences for such a system are shown in Fig. 2. Thus, measured phase differences between the three pairs of microphones give the direction (Θ) of the wavefront. A further measurement at a different location gives the source position.

Signal Processing System

The three condenser microphones type 4145 together with associated pre-amplifiers type 2619 are fixed to three tubes so that the lines joining them form an equilateral triangle whose sides are equal to half the anticipated wavelength. Power for the microphones is provided by a pair of 2804 battery driven power supplies mounted on the triangular support. The triangular frame work is fixed horizontally at its centre on a tripod whose legs rest on short radial extensions bolted on to a turntable. This arrangement is stable and enables controlled rotation of the array.

The signals from the three microphone/preamplifier assemblies are routed via long coaxial cables to the signal processing system. Each signal is handled separately in triplicated amplifier and filter sub-assemblies and, for simplicity, one channel only will be described, the other two being identical in every respect. A block diagram of the system appears in Fig. 3.

The signals from each of the three microphones are amplified by a low noise two stage amplifier providing an overall gain of 40 dB in the frequency range of 30 - 150 Hz. The selective response of the system to a given frequency is further enhanced by matched filters in each channel. The filter employs a twin - T notch filter in the feedback loop of a single operational amplifier and has a gain at resonance of 85 dB whilst the overall signal to noise ratio is 80 dB.

The signal from the filter is then fed to one of the phase sensitive voltmeters, another channel being fed with a signal originating from one of the other two microphones. Referring to the waveform sketches shown in Fig. 4, the two signals to be compared, A and B, are first squared, then clamped to eliminate the negative half cycles and subsequently applied to the Schmitt trigger inputs of a pair of one shot monostables. These produce a 100 ns pulse at their outputs every time the inputs receive a falling edge transition of the waveform. The pulse from one channel (A_3) is regarded as the reference, and an inverted pulse from the other channel is arranged to alternately set and then reset a flip-flop so that the length of time for which it is 'on' is determined by the spacing of the leading edges of the control pulses. The result is a pulse occurring every cycle whose duration is proportional to the temporal difference and hence to the phase difference between the two sinusoidal input signals ($\emptyset_{A:B}$).

In this way, channels 1 and 2, 2 and 3, and 3 and 1, are individually compared by three such phase detector circuits and the results are indicated on moving coil voltmeters scaled 0°- 360° and also recorded on a twin channel level recorder (type 2309) whose y-axis is similarly scaled.

In the interests of maximum power supply hum immunity the DC power supplies for all the system circuitry was derived from an accumulator via DC to DC power units employing two high frequency inverters and elaborate smoothing and shielding.

Validation of the Instrument

In order to evaluate the instrument, the array was tested in the field using a loudspeaker driven by an oscillator to simulate the source.

For one full rotation of the array, the measured phase variations for a pure tone whose level was between 10-12 dB above background are shown in Fig. 5. A comparison of these values with the calculated values of Fig. 3 shows the directional resolution to be accurate to within $\pm 2^{\circ}$.

Similar tests with narrow band noise of 10 Hz bandwidth centred on the pure tone also showed the expected variation of phase angle with the rotation of the array (Fig. 6). The directional resolution, however, was accurate only to within $\pm 5^{\circ}$.

Conclusions

(1) A three element portable microphone array and associated electronics has been constructed.
(2) The system is responsive to both pure tone and narrow band noise.
(3) The three element array does not suffer from the directional ambiguity that could be a problem in a two element system.

Acknowledgement: Thanks are due to Mr. A.D. Thomas for building the electronic circuits associated with the microphone array system.

References

(1) Vasudevan R.N. and Leventhall H.G., I.O.A. Low Frequency Noise Conference, January 1979. "Environmental Low Frequency Noise".
(2) Vasudevan R.N. and Gordon C.G., 1977, Applied Acoustics 10, p57-69. "Experimental Study of Annoyance Due to Low Frequency Environmental Noise".
(3) Barber N.F., Proc. of a Conference sponsored by the U.S. Naval Oceanographic Office and the National Academy of Sciences, 1961, p 137-150, Prentice-Hall, Englewood Cliffs, N.J., 1963. "The Directional Resolving Power of an Array of Wave Detectors in Ocean Wave Spectra".

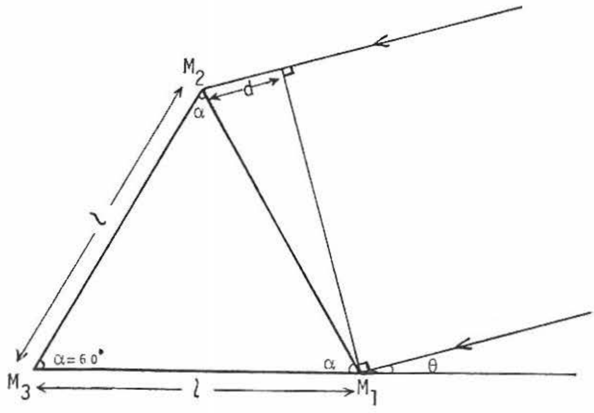


Fig.1 A Three Element Microphone Array

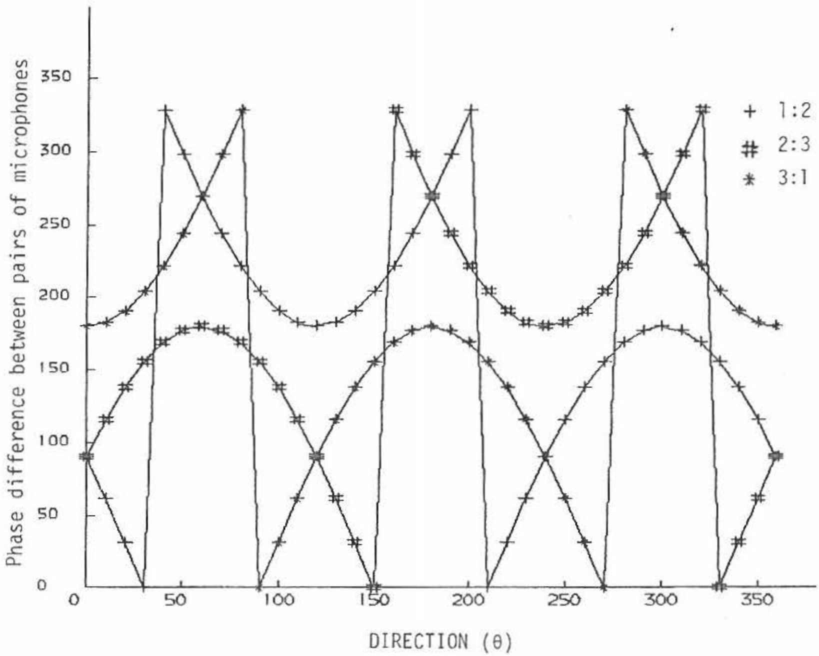


Fig.2 Calculated Phase Variations With θ

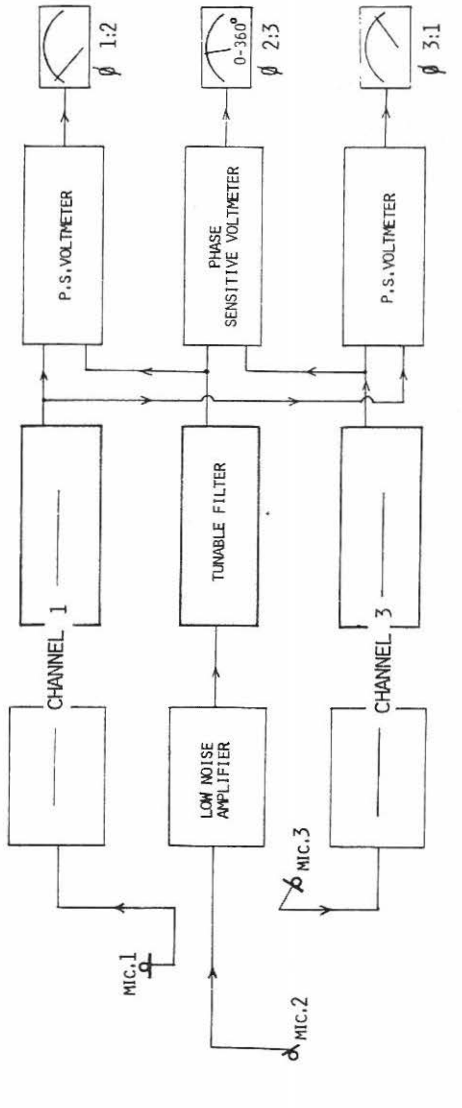


FIG.3 MICROPHONE ARRAY SYSTEM

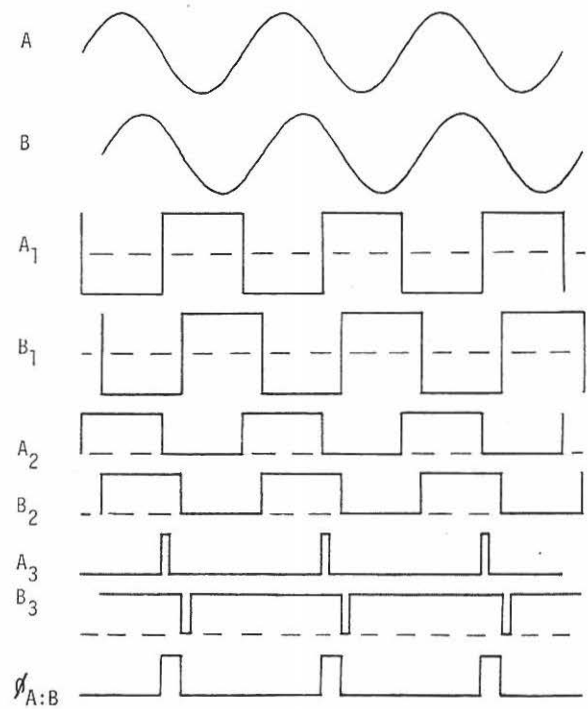


Fig. 4 Waveform Processing in the Phasemeter

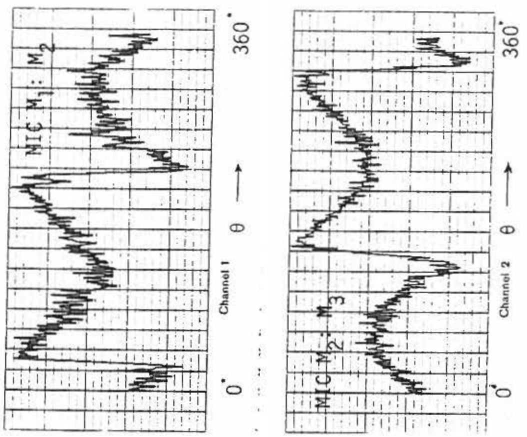


Fig.6 Measured Phase Variations for Narrow Band Noise

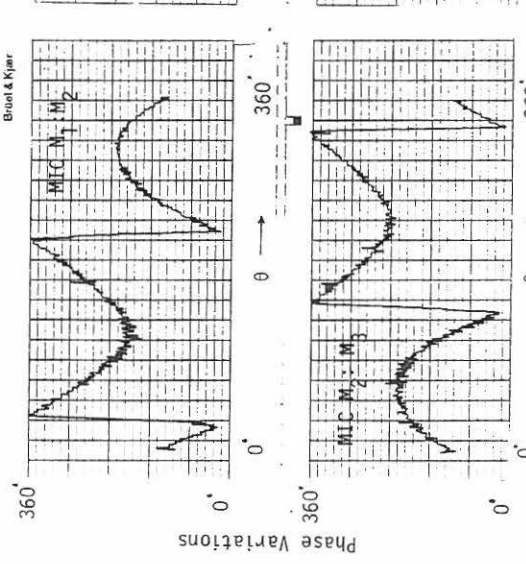


Fig.5 Measured Phase Variations for a Pure Tone

Conference on
Low Frequency Noise and Hearing

7–9 May 1980
at Aalborg University Centre
Aalborg, Denmark
Proceedings edited by
Henrik Møller and Per Rubak

SURVEY METHODS FOR LOW FREQUENCY NOISE IN VENTILATION PLANTS

Jörgen Svensson and Sven Tyrland, Ingemansson Acoustics,
Box 53037, S-400 14 Gothenburg, Sweden

Summary

This paper describes a pilot project carried out in order to find a suitable measurement technique for low frequency sound. The technique should allow rational data collection for the purpose of giving a statistical basis for the development of criteria for long-term exposure to low frequency noise. Different quantities describing the sound are used. Topics treated are frequency range, record length, weighting curve, momentary level distribution, measurement points, source detection etc.

Introduction

On a grant from the Swedish Council for Building Research, Ingemansson Acoustics are currently carrying out a pilot project on the measurement and analysis of low frequency noise from ventilation plants. The Council is also sponsoring a project on the influence of the ventilation plant configuration and construction on the low frequency noise levels, in which our company takes part [1].

These two projects aim towards effective methods for the technical data collection necessary for future studies of human response to long time low frequency noise exposure. Regarding measurements this involves questions about transducers, measurement positions and conditions, recording technique, filtering and analysis methods. It is also a matter of how we wish to present the low frequency sound impacting on a human being.

Quantification of low frequency sound

Little is known about the long term effects of infrasound, which may be pronounced also at lower levels than what can be derived from short time exposure tests. Also is the frequency range 20-80 Hz poorly covered by existing criteria. To find relevant criteria is a heavy task since many parameters are involved and not easily isolated. Nevertheless we must find answers to the questions being pronounced about infrasound.

In this situation it is important not to cling to a single way of describing the noise. As long as we are not familiar with the effects of long time infrasound exposure upon health and well-being, we have to carry with us several quantities describing the noise and manipulate them in different ways until we finally, on a statistical basis, hopefully find a reasonable correlation between one or a couple of quantities and the effects on man.

Measurement considerations

For practical reasons we must put some limits on the description of the low frequency sound pressure (or velocity). These limits are of major importance to the data collection speed and thus to the costs for finding the requested criteria. Below a few considerations are given on basis of the present state of the current projects.

Frequency range

From a series of measurements in mechanically ventilated rooms, the difference in low frequency power spectrum with ventilation on and off respectively has been averaged, see Fig. 1. Total number of measurements is 80, covering 10 different ventilation plants. The Brüel & Kjaer 2631 microphone carrier system has been used, reaching down to 0.01 Hz. Analysis of the FM-recorded signals has been performed with a Hewlett Packard 5420A FFT-analyzer. Resolution 0.02 Hz, corresponding to a filter bandwidth of 0.07 Hz.

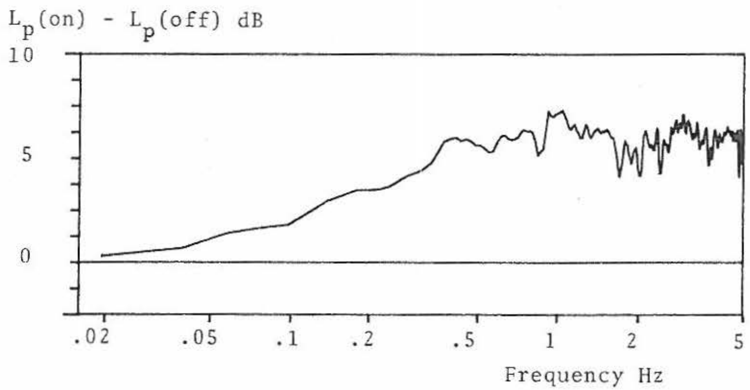


Fig. 1. Averaged difference in power spectra with ventilation fans on and off respectively. From measurements in 40 rooms.

It can be seen from Figure 1 that the ventilation plants will influence noticeably upon the infrasound levels down to about 0.2 Hz. That is, if the role of the mechanical ventilation is to be investigated, the frequency range should be extended down to 0.2 Hz. The low frequency break point is of vital importance since the spectrum is continously increasing towards the low end, as is examplified in Figure 2.

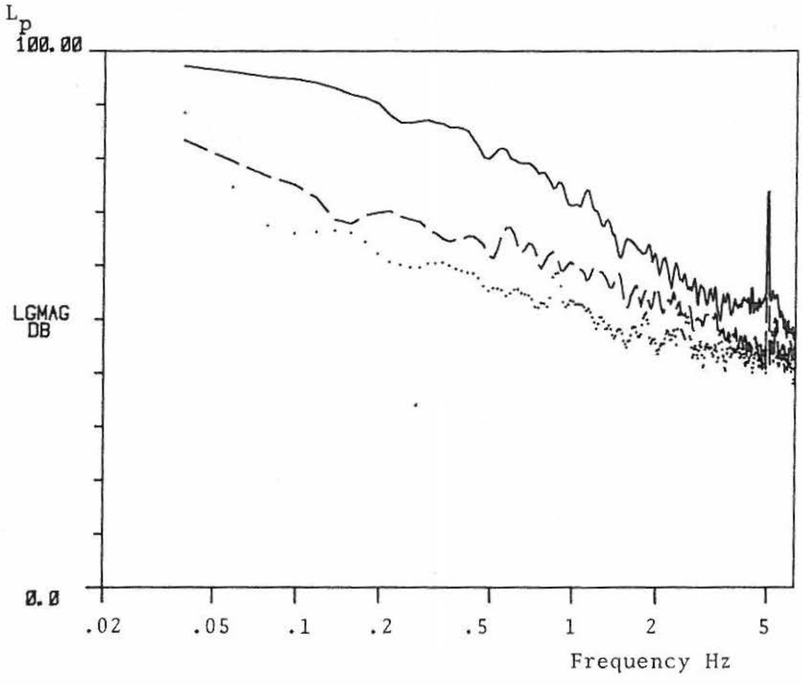


Fig. 2. Example of infrasound power spectra with ventilation ——— , and without ventilation ----. The dotted line shows the noise floor of the equipment, including the peak at 5 Hz. Resolution 0.02 Hz.

Sometimes total power within a frequency range is measured, as is the case considering the Swedish Regulations for Protection of Worker's Health. Here the Infrasound Level (dBIL) 2-20 Hz is used as a criterion. The importance of the low frequency filter band limit to the total power is shown in Figure 3. The figure suggest that the break point should be much lower than 2 Hz if we are anxious not to loose information which could be of interest when studying the human response.

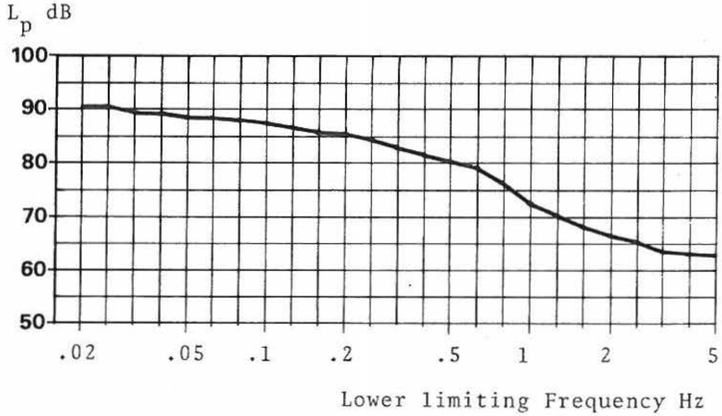


Fig. 3. Total power from an infrasound spectrum as a function of the low frequency filter band limit. High frequency limit is 20 Hz.

Record length

Assuming we need a smallest bandwidth of 0.1 Hz to detect slow variations in the static air pressure (infrasound), a record length of 160 seconds will give us a BT-product of 16. The rms error in dB will then be

$$\varepsilon = 20 \cdot \log\left(1 \pm \frac{1}{\sqrt{2BT}}\right) = \begin{cases} +\ 1.4\ \text{dB} \\ -\ 1.7\ \text{dB} \end{cases}$$

For these frequencies we may accept such an error as a resonable compromise between accuracy and speed.

Weighting curve

It may be of interest to see how the weighting curve suggested by P.V. Brüel [2] applies to measured infrasound spectra. Figure 4. shows this weighting curve filtering an average of 40 measured infrasound power spectra. It is obvious that levels at 0.2 Hz, 10 dB below maximum, are still of interest.

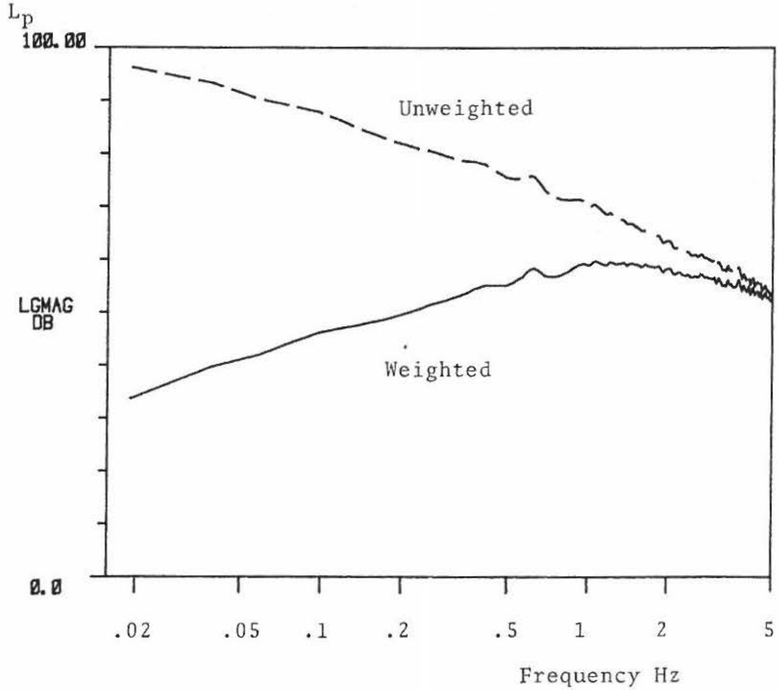


Fig. 4. Averaged infrasound power spectra from 40 rooms ----. D:o filtered through P.V. Brüel's weighting curve ——.

Momentary level distribution

The momentary level may play an important part regarding the human reaction to infrasound. Figure 5 shows what happens when the ventilation plant is turned on. The change in crest factor indicates that the equal energy concept should not stand alone when describing the low frequency sound. A treshold for the momentary level, to be exceeded only for a minor percentage of time, may be a form of criterion.

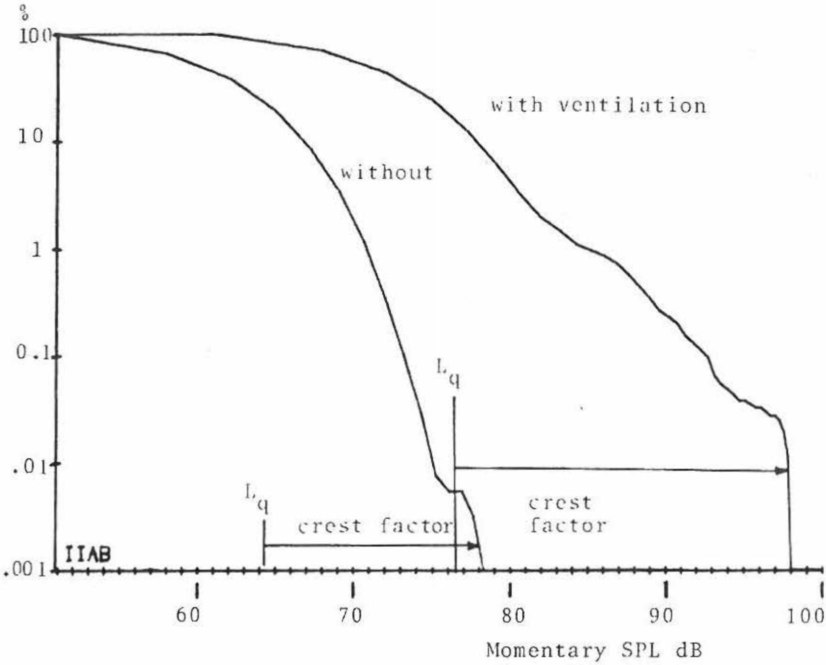


Fig. 5. Cumulative distribution plots of low frequency sound 2-80 Hz with ——— and without ----- ventilation fans running. The momentary level, sampled every 3 ms, is distributed as shown.

Microphone positions

For frequencies below the first room resonance, a position anywhere in the room may be used. For higher frequencies, we suggest a position in a corner of the room. This concept will be further investigated.

References

1 Stefan Einarsson: Infrasound in ventilation plants (this conference)

2 Per V. Brüel: Limits for Infrasound and Ultrasound in Factories. Inter-Noise 79, Warszawa 1979.

Conference on
Low Frequency Noise and Hearing

7–9 May 1980
at Aalborg University Centre
Aalborg, Denmark
Proceedings edited by
Henrik Møller and Per Rubak

Proposal on the low frequency noise meter

Yasuo TOKITA, Kazuo SHIMIZU
Kobayasi Institute of Physical Research
and Mitsuo OKUDA
Rion Company Ltd,
(3-20-41. Highashimotomachi Kokubunji, Tokyo 185 Japan)

Introduction

In Japan, during the last ten years or so, there have been many complaints for the low frequency noise or infra-sound. Sometimes, these spectra include the audible frequencies, but the levels of dB(A) are not so large, then the noise levels in dB(A) do not fit to evaluation of com-plaints.

In order to determin the frequency response of new type noise meter which evaluate low frequency noise, we have done some approach as follows;

1) According to the summarization of data, frequency and level range are determined.
2) The influence of low frequency noise for human life were devided into two categories; structural response of house construction and psychological or physiological effects on persons., and frequency responses were deter-

mined by fitting to those categories.

$.1 Frequency spectra related to low frequency noise complaints.

We have been summerized published data about low frequency noise complaints. These data re arranged in two categories, one is source spectra and the other is environmental field spectra which affect to inhabitants. The important property regard to low frequency noise complaints may be second category.

Fig.1 shows the rough sketch of these 1/3 octave band frequency spectra.

(a) e.g. Jumbo aircraft, large sized truck and bus.
(b) e.g. Blower, diesel engine, compressor and pump.
(c) e.g. Dam discharge, highway long brige and inrush to tunnel of high speed railway.

Generally, in the case of (a) in Fig.1, these noise contain higher frequency component, then these cases are able to regulate by noise regulation law with dB(A), as the values of dB(A) are determined by higher frequency component above 50 Hz. Sometimes, the case of (b) and (c) in Fig.1 are off controlled by dB(A).

Fig.2 indicates the low frequency noise spectrum at the point of 100 meters apart from jet burner in factory. According to noise regulation law, upper limit of this area(Industry area) is 60 dB(A). This noise level is about 57 dB(A), then this factory sutisfy the regulation law. But in the neighbouring house, the window is rattling when burner is on fire, and inhabitants complain about this rattling noise and unpleasant feelings.

In this case, linear sound pressure level is about 79 dB and C weighted level is about 74 dB, but those levels are not countered in regulation law.

As a result of survey, even though the dominant frequency region which complained on low frequency noise pollution is about 1 to 100 Hz, the noise would be able to regulate by dB(A) which contain above 50 Hz components. Then in order to evaluate the low frequency noise pollution, it would be need that evaluation meter has the frequency region up to 50 Hz.

From our survey, measureable range of level was need to contain about 50 to 120 dB in the case of environment.

$.2 Structural response of window and door related to low frequency noise complaints.

The most complaint about low frequency noise is vibration of window and door. Then the response of these by sound pressure is one of the evaluation term of complaints.

Fig.3 shows the minimum sound pressure level which generate rattling when sound pressure incident upon them. The rattling occure with the motion of panel between it and sill.

It would conclude from the experiment described above as follows.

1) Rattling occure in discrete frequencies.

2) Even though the type and weight are different, the minimum levels are all about 75 dB, and frequency ranges distribute about 5 to 10 Hz.

According to our field survey, this level coincide with structure complaint of inhabitants.

Then the sound pressure itself would correspond to evaluation number for structural complaints.

$.3 Frequency response of human being to evaluate the feeling.

In order to evaluate the low frequency complaint, it is necessary to determin the frequency response for human feeling.

We had considered that psychological and physiological effect would correspond to detection of low frequency noise, then the frequency response of detection threshold might be the standard response.

Fig.4 shows the average curve of infrasound and low frequency noise detection threshold for normal person within the limit of the literatures which we searched. But, this curve arranged without the case which reported about very sensitive persons. In this figure, A weight curve is arranged also. A slope of this average curve may be nearly equal to -12 dB/octave between 1 to 50 Hz.

$.4 Low frequency noise meter.

In spite of many problems remainning unsolved we propose new type low frequency noise meter to evaluate low frequency noise complaints with next suggestions.

1) Frequency range of flat response is from 1 to 50 Hz. This call "Low frequency sound pressure level" (LSPL) This range is used to evaluate the structural complaints and frequency analysis.
2) Weighting curve to evaluate human feeling is fall off at 12 dB per octave towards the lower frequency. This call "Low frequency sound level" (LSL)
3) At the upper and lower frequency end, the response are fall down with 18 dB per octave in order to count out a needless frequency component.
4) Dynamic response of indicater is slow of sound level meter.

Next is the example of specification of low frequency noise meter.

Measurement range	50 - 140 dB (0 dB = 20 μPa)
Frequency response	1 - 1000 Hz (SPL)
	1 - 50 Hz (LSPL)
(c.f. Fig.5)	12 dB/oct < 50 Hz <-18 dB/oct (LSL)
Microphone	Ceramic microphone
Meter	25 dB full scale

	True R.M.S.
	Peak of wave form and maximum level hold.
Out put	AC out put
Calibration	Built-in oscillator

$.5 Conclusion

In order to evaluate low frequency noise complaints in residents, new type noise meter had proposed. This proposal involves many problems to be solved. But at the first step, we are going to use this meter about field survey in Japan.

Reference

Survey report of Environment Agency(Japan) about infrasound and low frequency noise. 1977,1978,1979.

W.Tempest (ed) ; Infrasound and low frequency vibration (Academic Press. 1976)

Proceedings of Colloque International sur les Infra-sons 1973.

N.Broner ; Journal. sound & vibration 58(4)483 (1978)

H.E.von Gierke & D.E.Parker; Infrasound (Handbook of sensory physiology.Vol.V. Part 3, Springer Verlag)

N.S.Yeowart and M.J.Evans; J.A.S.A. 55, 814 (L974)

D.L.Johnson & H.E.von Gierke; Proceedings of Inter Noise '75.

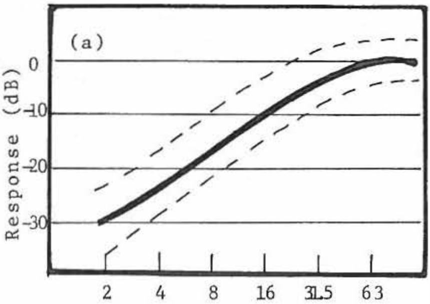


Fig.1 Rough sketch of low frequency noise spectra pattern related to low frequency noise complaints.

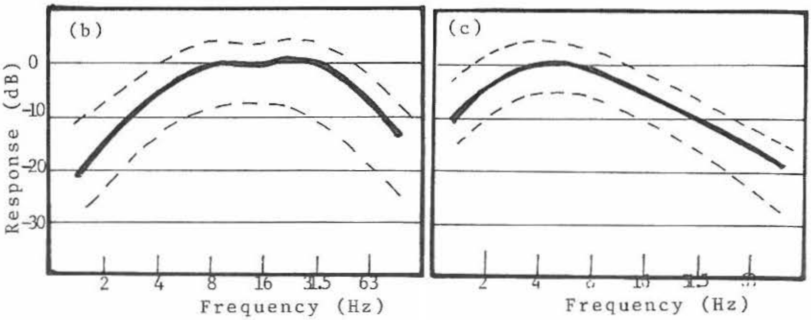
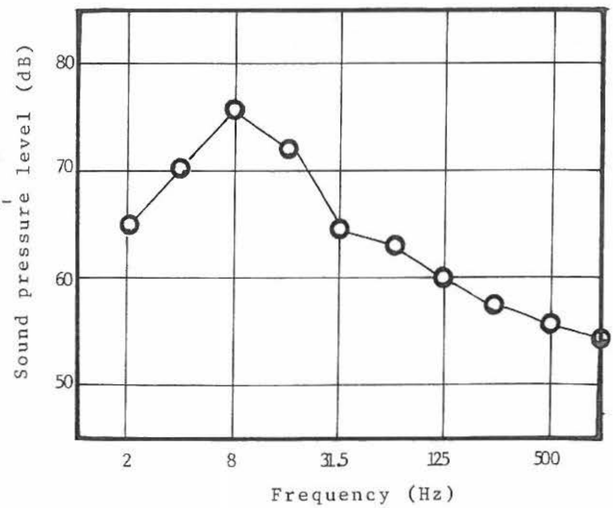


Fig.2 Example of low frequency noise. (Jet burner)



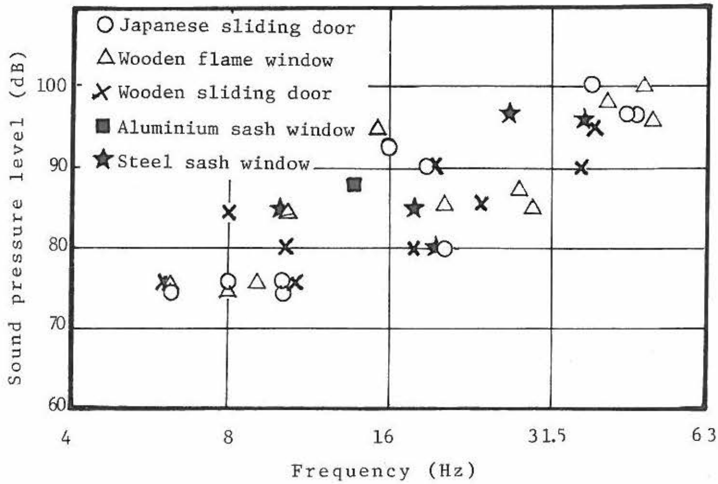


Fig.3 Minimum sound pressure level of rattling.

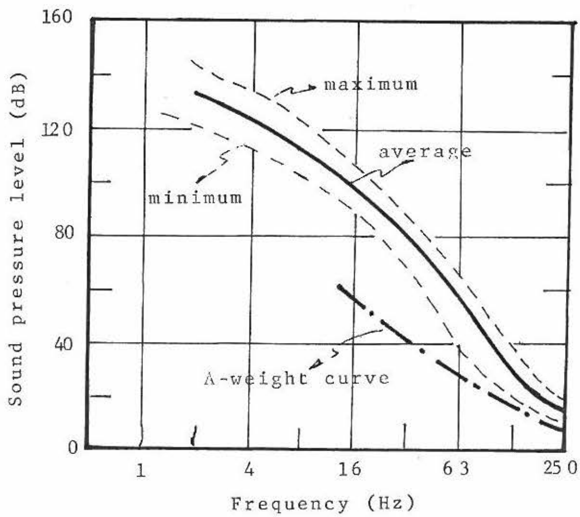


Fig.4 Infrasound and low frequency noise detection threshold and A weight curve of sound level meter.

Proceedings of the Conference on Low Frequency Noise and Hearing
7–9 May 1980 in Aalborg, Denmark

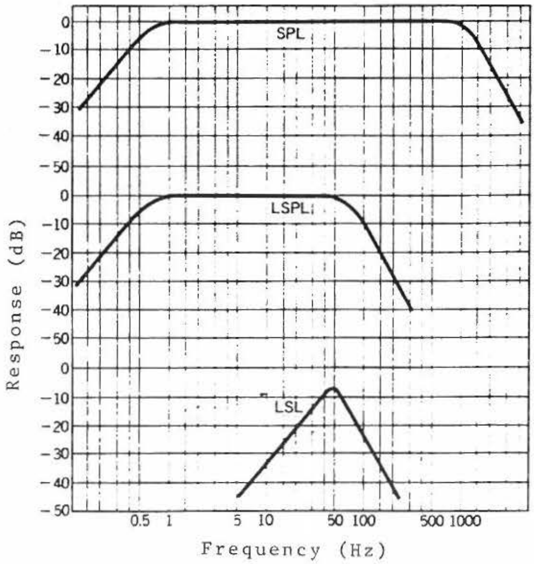


Fig.5 Proposed frequency response of low frequency noise meter.

Conference on
Low Frequency Noise and Hearing

7–9 May 1980
at Aalborg University Centre
Aalborg, Denmark
Proceedings edited by
Henrik Møller and Per Rubak

STANDARDIZATION FOR LOW FREQUENCY NOISE MEASUREMENTS

Per V. Brüel
Brüel & Kjær
Nærum Hovedgade 18
2850 Nærum
Denmark

During the last few years there has been an increasing interest in ascertaining whether possible damage to the human body can be caused by exposure to frequencies outside the audible range of 20 Hz to 20 kHz.

The possible effect of exposure to infrasound, which we will define as sound in the frequency range from 2 Hz to 30-50 Hz, has been the subject of intensive investigation during the last ten years. However, only in a few very extreme cases has a relationship between damage and exposure to infrasound been established on a firm scientific basis. Similarly in the case of ultrasound, which we define as sound at frequencies greater than 20 kHz, very little evidence of damaging effect has been documented.

Nevertheless, as a precautionary measure, some countries have included limits for maximum tolerable infrasound and ultrasound levels in their noise legislation. Sweden and Norway have already established limits for the maximum permissible level of infrasound and ultrasound in factories. In Sweden the defined infrasonic frequency range is from 2 Hz to 20 Hz, and the maximum permissible limit in Swedish factories for an eight-hour working day is 110 dB independent of frequency. The defined ultrasonic frequency range is from 20 kHz to 200 kHz, and the maximum 1/3-octave levels are: 105 dB for 20 kHz, 110 dB for 25 kHz, and 115 dB re 20 μPa for 31 kHz and all higher frequencies. The regulations in Norway should have become effective from 1980-01-01, but due to the increased criticism of the proposed legislation their introduction has been postponed until further notice, possibly awaiting action by ISO.

Since some countries are already deciding upon legal limits for both infrasound and ultrasound levels, it is imperative that some standardization is established. In the following, a suggestion for such an international standard is described.

When measuring infrasound it is fairly simple and straightforward to determine the sound pressure level in different frequency bands, thus giving a curve of sound level as a function of frequency. If these measuring results are to be used to determine permissible limits, one single figure or a few single figures are necessary. Consequently a weighting curve analogous to the A-weighting for the normal sound level meter is required. If such a weighting curve does not exist, the result would be similar to the legislation now in force in Sweden, where all infrasound frequencies are treated with the same weight.

It is apparent that if limits similar to those in force in Sweden are imposed on factories all over the world, it will be an extremely costly step, as sound pressure levels above 110 dB in the frequency range 2-5 Hz are very common. On the other hand, such restrictions are unnecessary, because sound pressure levels with that intensity at the low frequencies are way below the threshold curve and thus cannot possibly have any damaging effect on human beings.

In order to avoid such very costly and unnecessary regulations, ISO/TC 43 decided at its Stockholm meeting in May 1979 to establish a Study Group to investigate the possibility of forming and agreeing upon a weighting curve for both infrasound and ultrasound. The weighting curves should be formed so that less weight is given to those frequencies both in the infrasonic and ultrasonic frequency range which are less important than frequencies of 20 Hz and 20 kHz, respectively.

A Danish suggestion for a weighting curve with a slope of 6 dB/octave downwards for the low frequencies of the infrasonic range and upwards for the ultrasonic range was forwarded at the Stockholm meeting. The Study Group met in October 1979 in London and decided that it was unnecessary to draw up a weighting curve for the ultrasonic frequency range as indicated in the Swedish code of practice, i.e. from 20 kHz to 200 kHz, because all ultrasonic frequencies found in industries are mostly in the audible range or very rarely exceeding 40 kHz. Should occasionally frequencies between 20 and 40 kHz occur, it is extremely easy to screen for these frequencies.

In the infrasonic range it was agreed that a weighting curve was necessary and needed as a guidance for labor protection agencies in the different countries:

The threshold curve in the infrasonic range is well established, and this curve has a slope of 12 dB/octave towards low frequency. There was no doubt that a weighting curve following the threshold (i.e. the inverse) was required, and this has been designated curve "P". However, it was assumed that labor protection agencies in most countries would regard this curve as too steep, tolerating very high pressures between 2 and 4 Hz, especially as Sweden has established a flat curve. It was therefore suggested to introduce a curve of 6 dB/octave also, as indicated in the original Danish proposal. This curve has been designated curve "N".

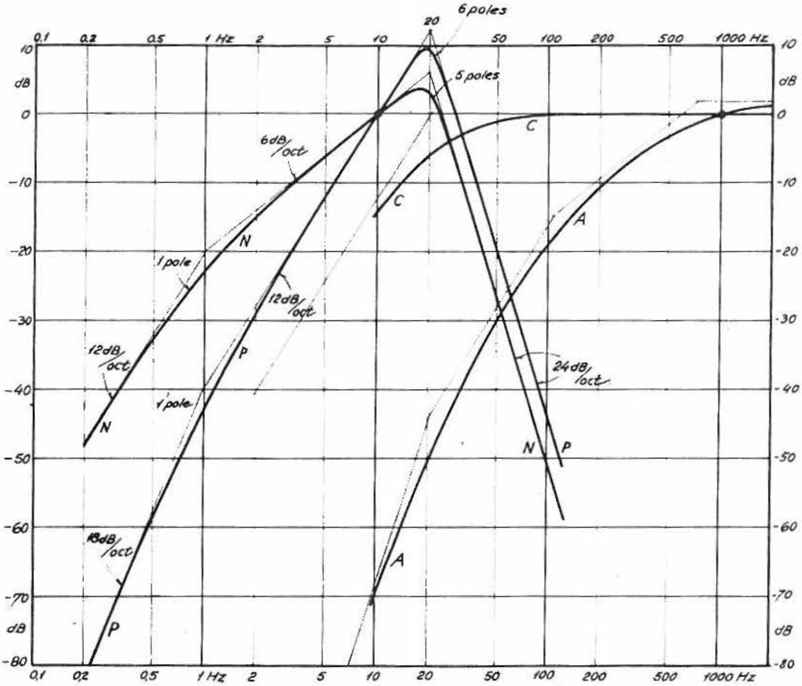
Another problem in defining a weighting curve was to have sharp cutoffs both at the low and especially at the high frequency end, because it is important that a sound measured with a normal sound level meter should not be recorded on an infrasound level meter. Therefore cut-offs in the audio range have been suggested to follow 24 dB/octave. At the low frequency end it is normally sufficient to say that the weighting curve must not bend upwards but should follow at least 6 dB/octave or steeper at the low end. In most cases a leakage in the microphone will be sufficient to give a suitable cut-off for the very low pressure variations.

The point where the curves bend into the audio range is also important, because there should be approximately the same gradient for the bend of the C-curve and the N-curve. Some people may ask why it should not go continuously over from the A-curve, and the answer is that all infrasound of interest has very high sound pressure levels, and consequently the form of the C-curve is most appropriate.

We already have limits in most countries for the highest noise levels based on the A-curve of the order of max. 85-90 dB(A), and the limits for infrasound should be made at such a level that a limit for 20,1 Hz based on the A-curve should be nearly the same as 19,9 Hz based on the N-curve.

The figure shows the curves which have been recommended by the Study Group. Dr. D.W. Robinson of NPL, Teddington, U.K., has made a proposal for a text for a recommendation, and it is hoped that this text can be close to the final recommendation.

Tolerances and the correct description of the P- and N-curves as well as all the requirements for a suitable infrasound level meter should be specified by IEC when ISO has agreed on the correct weighting curves. Limits have to be introduced in the different countries and need not be similar.



6 poles
5 poles
20
0.1
0.2
0.5
1 Hz
2
5
10
50
100
200
500
1000 Hz
10
dB
0
-10
-20
-30
-40
-50
-60
-70
-80
6dB/oct
12dB/oct
1 pole
12dB/oct
1 pole
18dB/oct
24dB/oct
N
P
C
A

Fig.1.

Conference on
Low Frequency Noise and Hearing

7–9 May 1980
at Aalborg University Centre
Aalborg, Denmark
Proceedings edited by
Henrik Møller and Per Rubak

ATTENUATION OF LOW FREQUENCY NOISE USING REACTIVE SILENCER TECHNIQUES

P.F. Chatterton B.Sc., Ph.D., M.I.O.A. *
R.M. Taylor M.I.O.A. *

* Rupert Taylor & Partners Ltd 374 Edgware Road, London W2 1EB, England

SUMMARY

This paper concerns itself with a particular case of a low frequency noise problem arising from the operation of an industrial forced draught fan boiler, affecting residents in a nearby residential property. The nature of the noise source is described, together with the method by which the noise was assessed, highlighting the inadequacy of the A-weighting network as a means of determining annoyance due to low frequency noise. A reactive silencer of the resonating type was designed to attenuate the 30 Hz tonal peak which was emanating from the air intake of the forced draught fan, giving an attenuation of 30 dB at the peak frequency.

INTRODUCTION

A case history of a low frequency noise problem is presented, the paper describing the initial assessment of the noise problem using the British Standard 4142 " Method of Rating Industrial Noise Affecting Mixed Residential and Industrial Areas " 1967 (revised 1975) which employs the A-weighted sound level, and then describes the mechanisms of the production of the 30 Hz tone from an industrial forced draught fan boiler, and the means by which the noise was attenuated, using a resonating silencer.

The boiler in question is one of four industrial forced draught fan boilers with rotary cup burners, operating on an automatic sequence with two in operation at any one time, whilst maintenance is carried out on the third. The fourth boiler is lower rated and retained mainly for summer use.

Complaints were received from the owner of an adjacent residential property, some 50 metres distance form the boiler house, describing the noise as being of a low frequency throbbing type of noise. The owner was most concerned about the continual presence of the noise which he reported as giving rise to headaches and pains in the neck, also making sleeping difficult.

Visits to the house had been made by various interested parties, however listening tests over a short time period tended to give less adverse reaction to the noise than those taken over a longer period.

MEASURED NOISE LEVELS

The nature of the noise problem was a tonal peak at approximately 30 Hz, apparent throughout the whole of the house, though standing wave effects gave rise to considerable variation in level. The exact frequency of the peak varied between 30 and 33 Hz and was apparent over long periods including throughout the night-time period. The recorded levels in the bedroom and living room were 62 and 67 dB Linear respectively. Outside, the level rose to 79 dB Linear and within the boiler house the reverberant level was 85 dB Linear.

Measurements of the noise levels were taken using a CEL Sound Level Meter Type 175, coupled to a Spectral Dynamics Micro FFT Real Time Analyser Type SD 340, a permanent graphical record being obtained using a Hewlett Packard X–Y Plotter Type 7015A. The analyser is particularly useful for such field work in low frequency noise cases, giving a rapid print-out of the frequency spectrum. Set at a frequency range of 0 – 100 Hz, the 400 line resolution gives a frequency resolution of 0.25 Hz, the spectra being averaged over eight samples. Diagram 1 illustrates the spectrum recorded in the living room of the residential property, showing the peak at a frequency of 30.5 Hz.

Initial measurements carried out by various parties using an ordinary A-weighted sound level meter obviously did not register any significant reading of the 30 Hz tone (the A–weighting correction at this frequency being 40 dB) as higher frequency noise dominated the overall A-weighted value. This factor did not help the owner of the residential property in a speedy solution to the noise problem .

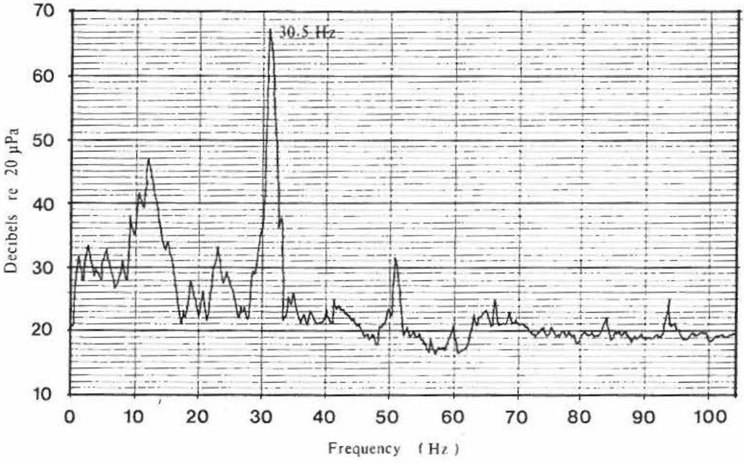


DIAGRAM 1 Spectrum of noise level within living room of residential property

ASSESSMENT OF NOISE LEVELS

The owner of the residential property tried, over a period of many years, to get the owner of the boilers to reduce the noise level within his property. However, this had little effect and in the end he resorted to legal action. Rupert Taylor & Partners Ltd were called in as consultants to assess the noise problem as affecting the resident. In such a mixed residential and industrial area, courts and local authorities consult the British Standard 4142 "Method of Rating Industrial Noise Affecting Mixed Residential and Industrial Areas" 1967 (revised 1975) for guidance as to the likelihood of complaints from the public. The Standard compares the predicted noise level, corrected for tonal, impulsive and intermittency and duration characteristics, with the background level in the absence of the noise of interest. An excess of 10 dBA or more is considered as being "likely to give rise to complaints", whilst an excess of 5 dBA is considered as being "of marginal significance". The Standard can also be used for assessing the justification behind existing complaints.

In particular cases of low frequency noise, the Standard can underestimate the degree of annoyance experienced. For such low frequencies, building structures can offer little attenuation, resulting in relatively high indoor noise levels compared with those outdoors. If in such a case the outdoor background noise level is high, the Standard, which is intended for use at outside positions, may well conclude that there is no cause for complaint, though indoors the excess of the offending source noise level above the background may be much higher due to the higher attenuation of the (higher frequency) background noise. Additionally, the Standard uses the A-weighted sound level, which normally serves as a useful indication of people's subjective reaction to sound for many sources of noise (e.g. road traffic noise), however it is questionable as to how suitable the A-weighting network is for purposes of assessing low frequency noise problems. The observation that low frequency noise (below 100 Hz) causing annoyance and disturbance to an extent that is not simply related to loudness has already been made. Tempest [1] reports results of investigations of man-made noise spectra that are high in energy content below 100 Hz and concludes that the A-weighting scale is inadequate in the prediction of adverse reaction to noise for frequencies below 100 Hz and, in particular, that an adverse reaction to sound that is quite different from loudness is obtained for frequencies below 32 Hz and describes this as a disturbance or unease.

In the particular case of interest the resident was lucky in that the background level was low and an assessment according to the British Standard 4142 concluded that "complaints may be expected". He obtained an injunction against the Regional Health Authority requiring them to abate the nuisance. The measured A-weighted level outside at the frequency of interest was 37 dBA which fell to 27 dBA in the lounge. Use of the equal loudness curves for the lounge position gave a value of 20 phons.

IDENTIFICATION OF NOISE SOURCE

Tests were carried out to identify the exact source of the noise and it was found that there was no significant radiation from the stack, this being achieved by plotting out the sound level at various distances from the stack, including where large screening existed and it was concluded that the source was at ground level. This process eliminates the need to take a microphone to the top of the stack . It was found that the noise emission was from the air intake opening, giving a value of 90 dBLinear at 0.5 metre distance. An absorptive silencer was fitted to the air intake in order to attenuate the higher frequency noise within the boiler house, however this had little effect on the low frequency noise around 30 Hz. The problem mainly arose from the method of operation of the fan and dampers in controlling the the air intake, the fan always running at the maximum setting and the dampers being used to control the air outlet for various boiler settings. This mode of operation causes air turbulence and radiation of the 30 Hz peak. The maximum radiation occured at the idling setting of the boiler when the dampers were closed. It was also found that increase of the boiler setting marginally increased the frequency of the peak, covering a range between 30 and 33 Hz.

ATTENUATION OF THE 30 Hz PEAK

Conventional, off-the-shelf silencers were initially considered for reducing the emission at 30 Hz however, there were limitations firstly in providing sufficient attenuation, secondly in there being a limited amount of space available for the silencer and thirdly ensuring that the back pressure was kept to a minimum.

The most obvious choice of silencer for such a tonal sound is the side branch resonator type. This reactive type of silencer allows free flow of air, whilst impeding the transmission of sound at a particular frequency. The dimensions of the main duct, tubes and resonating volume are critical in determining the performance of the silencer. The transmission loss of such a silencer is given by the following:

$$\text{T.L.} = 10 \text{ Log} \left[1 + \frac{(D + 0.25)}{D^2 + B^2 \times \left(\frac{f}{fo} - \frac{fo}{f} \right)^2} \right] \qquad \text{...... (1)}$$

where:

D = resonator resistance (dimensionless) = $\frac{R \times A}{Ao \times p \times c}$ ...... (2)

B = resonator reactance (dimensionless) = $\frac{A \times c}{2 \times \pi \times fo \times V}$ ...... (3)

fo = resonant frequency of resonator (Hz)
V = volume of resonator (cu metres)
A = main duct cross sectional area (sq metres)
Ao = total aperture hole area (sq metres)
n = number of tubes
p = density of air (kg/sq metre)
c = speed of sound (m/sec)
R = acoustic resistance (N-sec/cu metre)

The resonant frequency of the silencer is given by:

$$fo = \frac{c}{2 \times \pi} \times \left(\frac{Ao}{V x t^1} \right)^{0.5} \qquad \text{...... (4)}$$

where:

$$t^1 = t + 0.8 \times \sqrt{\frac{Ao}{n}} \qquad \text{...... (5)}$$

t = length of tubes (metres)

A computer program was used to calculate the transmission loss curves for the resonator, the program calculating the attenuation for given spatial limitations. According to Beranek [2] the value of the resonator reactance, B should not be below 0.5 (equivalent to the assumption that the resonator dimensions are small compared to a wavelength). However, it is clearly preferable that B should be as low as possible in order that the maximum attenuation is obtained. A value of 0.23 was chosen and the predicted transmission loss is shown in Diagram 2. The two curves show that decreasing the value of B from 0.5 to 0.23, gives a further increase of 15 dB to the attenuation at theresonant frequency. The final design of the resonator also differed from the classic side branch resonator in that the resonating volume surrounded the main duct. Diagram 3 illustrates the design of the silencer showing it in section and cross section.

The resonant frequency of the silencer was designed to correspond to the sound emission at the idling setting of the boiler as the maximum noise was emitted at this setting. The performance of the silencer obviously decreases with the increase of the boiler setting (and

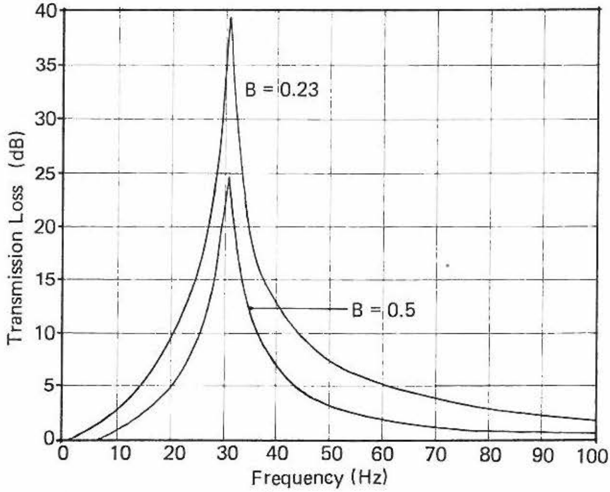


DIAGRAM 2 Predicted transmission loss of resonating silencer

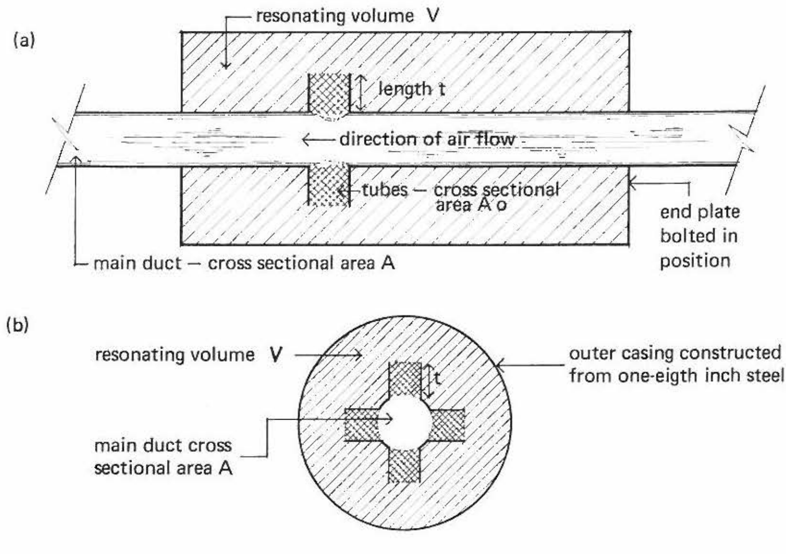


DIAGRAM 3 (a) Section through resonating silencer
(b) Cross-section through resonating silencer

subsequent increase in frequency of the emitted tone). This is offset by the decrease in emitted level. The end plate of the silencer was designed to be removeable in order that the resonating volume could be decreased in case of constructional errors, thus giving the flexibility for tuning the silencer. The material used for construction was one- eighth inch steel, which was chosen in view of the low frequency of the noise source. Care was also taken in calculation of the adverse effects that the tail-pipe could give, as in some instances an incorrect choice of tail-pipe dimensions could offset the high transmission loss at the resonant frequency.

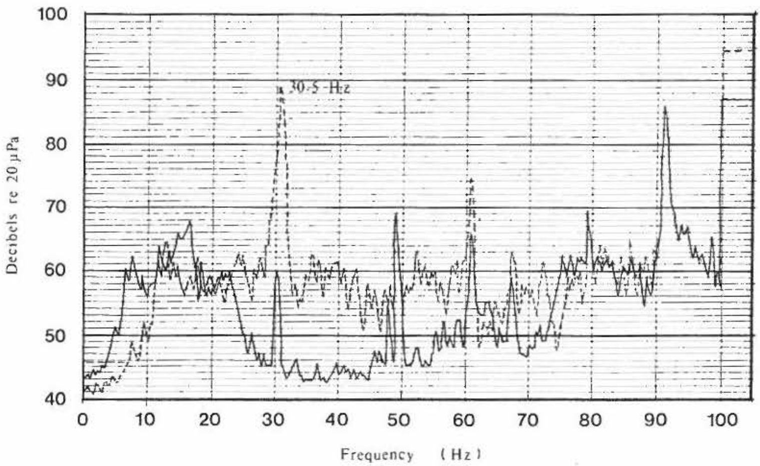


DIAGRAM 4 Spectra at 0.5 metres distance from air inlet – boiler idling

(a) absorptive silencer only in position
(b) absorptive and resonating silencer in position

RESULTS

Tests carried out before and after installation of the resonating silencer enabled the silencer performance to be determined. Diagram 4 illustrates the measurements taken at a distance of 0.5 metres from the air intake with the boiler at idling setting. The corresponding attenuation was obtained in the adjacent residential property. The level of 60 dB at 30.5 Hz was increased by 6 dB for one particular setting of the boiler (setting 3 in a range of 10), due to the increase in frequency of the peak, though the boiler operates for a limited period on this setting when on an automatic routine. This reduction in noise level was sufficient to remove the nuisance problem in the residential property.

REFERENCES

[1] Tempest " Loudness and Annoyance Due to Low Frequency Sound " Acustica Vol 29 1973 pp 206 – 209

[2] Beranek " Noise Reduction " Mcgraw-Hill Book Co Inc 1960

Conference on
Low Frequency Noise and Hearing

7–9 May 1980
at Aalborg University Centre
Aalborg, Denmark
Proceedings edited by
Henrik Møller and Per Rubak

DESIGN OF MEMBRANE ABSORBERS

Ulrik Danneskiold-Samsøe
Ødegaard & Danneskiold-Samsøe K/S
Lille Strandvej 19
DK-2900 Hellerup

Many types of industry are annoyed by low frequency noise, which for example is the case in foundries, ships, power plants, and in the concrete industry. Membrane absorbers can be used for the abatement of those annoyances, and the Danish Council of Technology has financed a study [1] of how to design the absorbers to make them as efficient as possible.

By perpendicular incidence of a plane wave the absorption coefficient α can be written as

$$\alpha = 1 - \left|\frac{Z_{ab} - Z_{st}}{Z_{ab} + Z_{st}}\right|^2 \qquad (1)$$

where Z_{ab} and Z_{st} are the specific impedance and the specific radiation impedance of the membrane absorber, respectively.

The specific impedance Z_{ab} can - with the cavity depth t and the propagation constant within the cavity γ - be written as the sum of the contributions from the membrane plate and the cavity filled with mineral wool. At low frequencies [2] it can be written that

$$Z_{ab} = 2M\omega\eta_m + jM\omega + \frac{\rho c^2}{j\omega}\gamma \coth(\gamma t) \qquad (2)$$

where M is the mass of the plate per square unit and η the loss factor of the frame-mounted plate without a cavity behind.

The propagation constant γ can for low frequencies [2] be written as

$$\gamma \simeq j\frac{\omega}{c}\left(1 - \frac{jr}{2\omega\rho}\right) \qquad (3)$$

$$= \frac{\omega}{c}\left|\left(-\tfrac{1}{2} + \tfrac{1}{2}\left(1 + \left(\frac{r}{\omega\rho}\right)^2\right)^{\frac{1}{2}}\right)^{\frac{1}{2}} + j\left(\tfrac{1}{2} + \tfrac{1}{2}\left(1+\left(\frac{r}{\omega\rho}\right)^2\right)^{\frac{1}{2}}\right)^{\frac{1}{2}}\right| \qquad (4)$$

and for $r \to o$

$$\simeq \frac{r}{2\rho c} + j\,\frac{\omega}{c}\left(1 + \tfrac{1}{2}\left(\frac{r}{2\omega\rho}\right)^2\right) \qquad (5)$$

where r is the flow resistivity of the mineral wool.

By various calculations it can be shown that (2) can be converted into

$$Z_{ab} = \rho c \ (R_o + j\beta) \tag{6}$$

where

$$R_o = \frac{1}{\rho c} \ (2M\omega\eta_m + h\rho c) \tag{7}$$

$$\beta \doteq \frac{1}{\rho c} \ (\omega M - \frac{\rho c^2}{\omega t} g) \tag{8}$$

$$h = h(\omega, r, t)$$

$$= \frac{\sinh \frac{rt}{\rho c} - \frac{r}{2\omega\rho} \sin \frac{\omega t}{c}}{\cosh \frac{rt}{\rho c} - \cos \frac{2\omega t}{c}} \tag{9}$$

$$\simeq \frac{rt}{3\rho c} \qquad \text{for } r \to o \tag{10}$$

$$g = g(\omega, r, t)$$

$$= \frac{\frac{rt}{2\rho c} \sinh \frac{rt}{\rho c} + \frac{\omega t}{c} \sin \frac{2\omega t}{c}}{\cosh \frac{rt}{\rho c} - \cos \frac{2\omega t}{c}} \tag{11}$$

$$\approx 1 - \frac{2}{3} \ (\frac{\omega t}{c})^2 \quad r \to o \tag{12}$$

The quantity R_o is thus the sum of the normalized losses in the plate and the cavity.

The specific radiation impedance Z_{st} can be written as

$$Z_{st} = \rho c(\xi + j\psi) \tag{13}$$

and in order to obtain the maximum coefficient of absorption the following equations must be satisfied:

$$\xi = R_o \tag{14}$$

$$\psi = \beta \tag{15}$$

With reference to Rindel [3] it is possible to calculate ξ by means of function in fig. 1 where

$$a = \frac{\sqrt{S}}{2}$$

and S is the area of the membrane plate, and k is the wave number. The flow resistivity r is taken from fig. 2.

Equation (15) is the resonance condition, and for an infinite stiff piston in a wall it can be shown [4] that

$$o \leq \psi < 0{,}7$$

Because the resonance condition is

$$\psi = \frac{1}{\rho c}\left(\omega M - \frac{\rho c^2}{\omega t} g\right) \tag{16}$$

$$\omega = \frac{\rho c t \psi \overset{+}{(-)} \sqrt{(\rho c t \psi)^2 + 4tgM\rho c^2}}{2Mt} \tag{17}$$

$$\simeq c\,\frac{\sqrt{t\rho g M}}{Mt} \tag{18}$$

for $\psi < 0{,}7$ and normal values of t and M

$$\simeq \sqrt{\frac{\rho c^2}{Mt}} \tag{19}$$

for $g \rightarrow 1$

which is the normal formula for calculation of the resonance frequency.

For simplicity ψ is negligible, and (15) can be converted to

$$\beta = o \tag{20}$$

Combining (6) and (13) with (1) one gets

$$\alpha = 1 - \left|\frac{R_o - \xi + j(\beta - \psi)}{R_o + \xi + j(\beta + \psi)}\right|^2 \tag{21}$$

$$= \frac{4(R_o\xi + \beta\psi)}{R_o + \xi)^2 + (\beta + \psi)^2} \tag{22}$$

Values of $\psi > o$ will give higher values of α than $\psi = o$. Conservatively ψ is therefore put as $\psi = o$.

Hence (21) is converted into

$$\alpha = \frac{4 \quad R_o\xi}{(R_o + \xi)^2 + \beta^2} \tag{23}$$

The highest absorption of resonance is $\alpha_{max} = 1$, which is obtained when (14) and (20) are satisfied.

Besides the absorption coefficient α it is also of interest to know the bandwidth Δf. Provided $\Delta f << 2f_{res}$ it can be shown that

$$\Delta f \simeq \frac{\rho c}{2\pi M}(R_o + \xi) \tag{24}$$

A lightweight plate and high losses give a broad bandwidth.

The rule-of-thumb for getting a high value of α is therefore to try to satisfy (14) but this will cause a small value of Δf. This quantity can be increased by increasing the losses but this change will at the same time cause a decrease in α_{max}.

The method of calculating R_o has been verified by means of experimental measurements of reverberation time per 1/3 octave band. The measurements were carried out both on a frame-mounted plate without a cavity behind, and on the same frame-mounted plate fixed to a wall with mineral wool in the cavity.

The former measurement gave a calculation of $R_o = 0,28$, where the parameters were $M = 2,7$ kg/m^2, $t = 0,05$ m, $\eta = 0,006$, $S = 1$ m^2, and $r = 5000$ Ns/m^4.

The latter measurement gave a direct measured result of $R_o = 0,30$. Both measurements were carried out in the 160 Hz 1/3 octave band because $f_{res} = 163$ Hz.

References

1 : Ulrik Danneskiold-Samsøe: "Udformning af membranabsorbenter". Enviroplan A/S. September 1976.

2 : Heckl & Müller: "Taschenbuch der Technischen Akustik". Springer Verlag 1975.

3 : J.H. Rindel: "Transmission of Traffic Noise through Windows". Laboratoriet for Akustik. Lyngby 1975.

4 : Heinrich Stenzel: "Die Akustische Strahlung der Rechteckigen Kolbenmembran". Acustica, (2) 1952 p. 263-281.

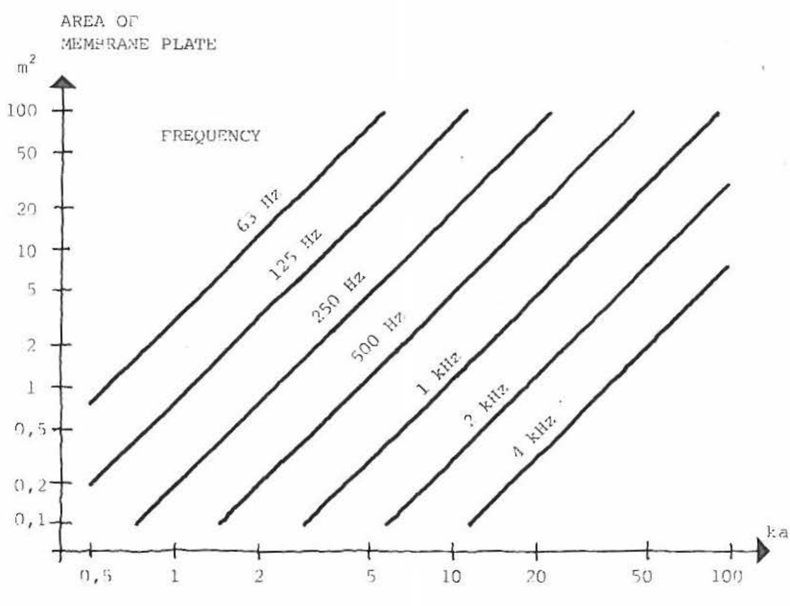

AREA OF
MEMBRANE PLATE
m²
FREQUENCY
63 Hz
125 Hz
250 Hz
500 Hz
1 kHz
2 kHz
4 kHz
100
50
20
10
5
2
1
0,5
0,2
0,1
ka
0,5
1
2
5
10
20
50
100

FIGURE 1a.

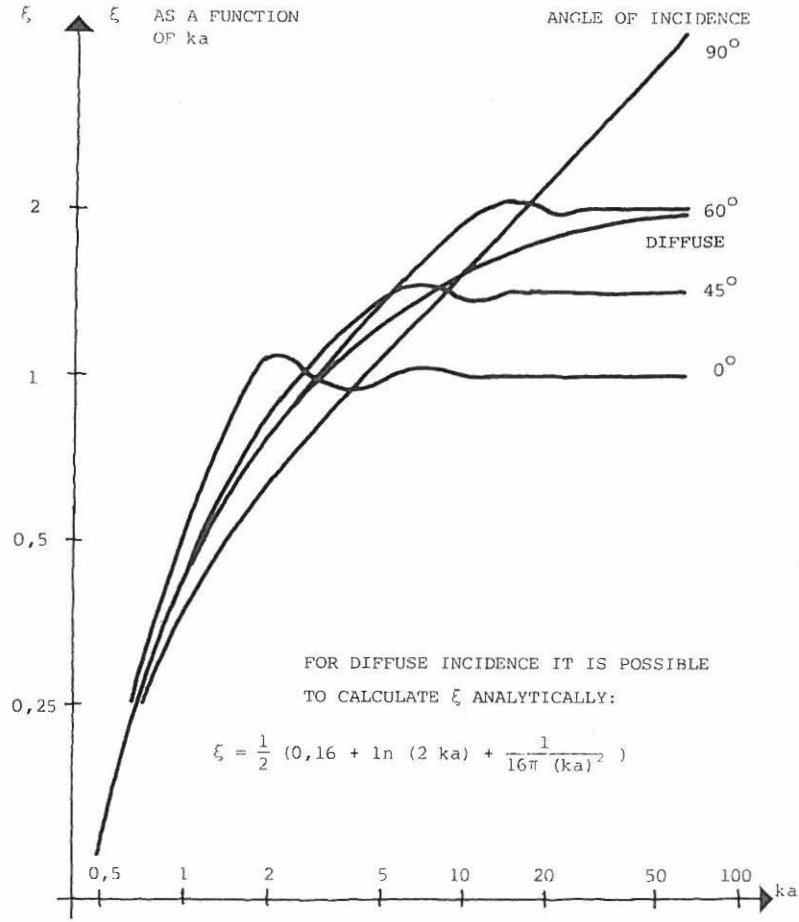

ξ
ξ AS A FUNCTION OF ka
ANGLE OF INCIDENCE
90°
60°
DIFFUSE
45°
0°
2
1
0,5
0,25
FOR DIFFUSE INCIDENCE IT IS POSSIBLE TO CALCULATE ξ ANALYTICALLY:
$\xi = \frac{1}{2}\left(0{,}16 + \ln(2\,ka) + \frac{1}{16\pi\,(ka)^2}\right)$
0,5
1
2
5
10
20
50
100
ka

FIGURE 1b.

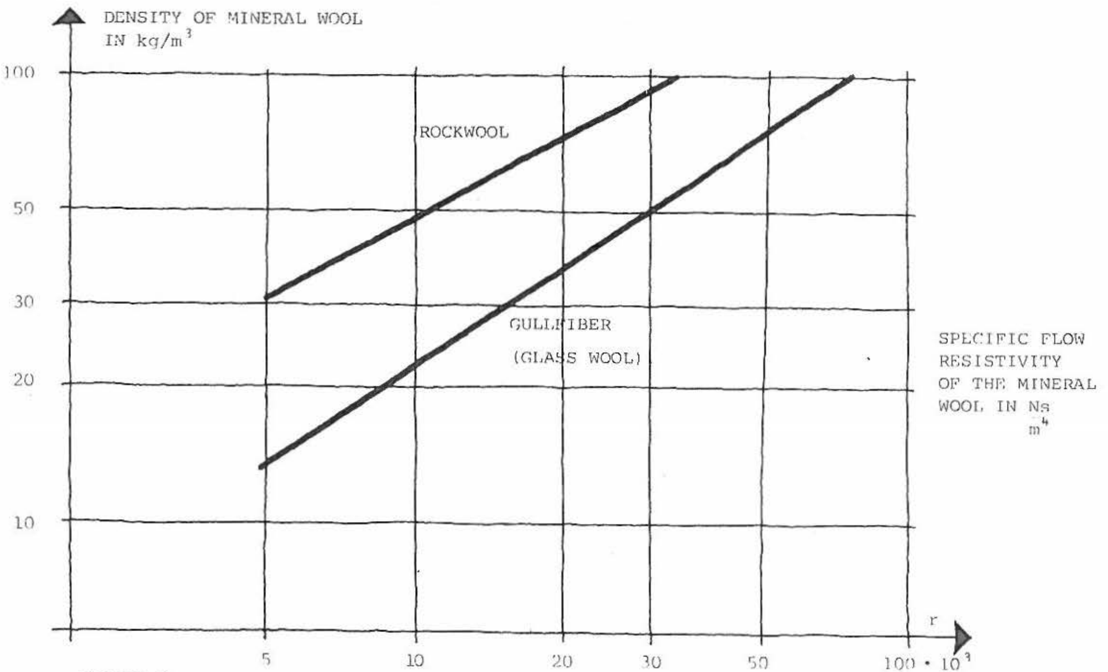


FIGURE 2.

The specific flow resistivity r as a function of the density of Rockwool and Gullfiber (glass wool)

Reference: "Akustisk val av densiteten hos mineralull". Report TR72-6, Lunds tekniske Højskole, Sweden.

Conference on
Low Frequency Noise and Hearing

7–9 May 1980
at Aalborg University Centre
Aalborg, Denmark
Proceedings edited by
Henrik Møller and Per Rubak

Sound Insulation in Buildings Within the Frequency Range 50-100 Hz

Per Kruppa and Laurids Østergård,
The Jutland Technological Institute,
135, Marselis Boulevard, DK-8000 Århus C

Summary

By an investigation of the sound insulation of windows with regard to traffic noise it has been established that sound transmission in the frequency range 50-100 Hz is predominant for some constructions. In the case of light party walls and floors it can likewise be established that the sound insulation of the constructions in the frequency range below 100 Hz determines the actual sound insulation. In the light of this, it seems disadvantageous that international standards only prescribe measurings of the sound insulation of building elements in the frequency range 100-3150 Hz.

Introduction

In connection with a number of consultative tasks the Institute has noted that in some cases there is bad correlation between the subjective perception of the sound conditions and the objective measuring results. It is our opinion that the reason for this in some cases is the sound transmission in the frequency range below 100 Hz.

The acoustic frequency range when measuring airborne sound insulation and impact sound insulation in buildings is traditionally 100-3150 Hz. The ISO-standard 140, parts I-VIII, which has just been adopted, does in fact also recommend that measurings are carried out in this frequency range. The same applies to ISO R 717 which is being revised at present.

Of course, tradition is not the only reason for this - the problems connected with obtaining adequate measuring accuracy at low frequencies by normal room sizes are also a decisive factor. The limited frequency range particularly gives problems by façade constructions as the noise from major vehicles such as lorries and buses has a high energy content in the low-frequency range. This problem is increased concurrently with the development of the public traffic.

In connection with a major investigation on measuring sound insulation against traffic noise for a large number of different window constructions the Institute has therefore also investigated the conditions in the frequency range 50-100 Hz.

Investigation of the sound insulation of windows

The investigation was carried out on behalf of the Danish Environmental Board. The purpose was to investigate the extent to which the sound insulation and heat insulation could be improved in an existing, old building. The measurements have been carried out in accordance with ISO 140, part V, traffic being the source of noise. The noise level outside the building was registered by means of a microphone at a distance of 2 m from the window, (fig. 1). The noise level in the measuring room was registered in six fixed microphone positions as the noise from a rotating microphone boom turned out to have an influence on the measuring result by window constructions with high sound insulation. The noise was tape-recorded and analysed in the analysis setup, shown in fig. 2.

When choosing the measuring objects, efforts were made to maintain the existing façade solution to the greatest possible extent.

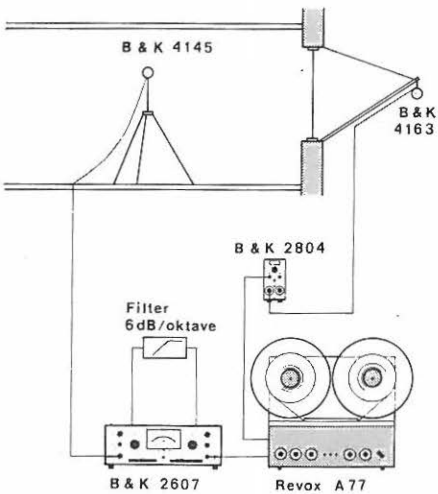


Fig. 1, measuring setup

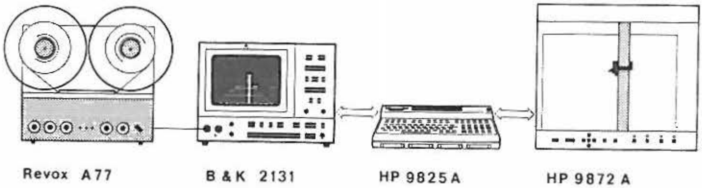


Fig. 2, analysis setup

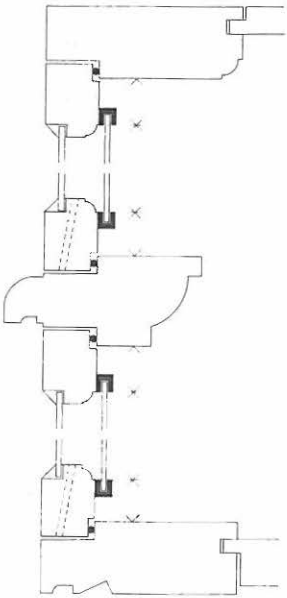


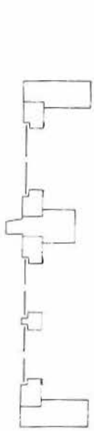
Fig. 3
Vertical section in the original construction with single pane mounted in plastic lists

Fig. 3 shows the simplest improvement of the construction consisting of a single pane mounted in plastic lists on the existing frame.

In fig. 4 some of the tested constructions with the corresponding measuring results are shown schematically. The measured I_a-values, determined in accordance with ISO 140 (frequency range 100-3150 Hz), are indicated in the figure. $\Delta L(A)_{eq,100-3150\ Hz}$ and $\Delta L(A)_{eq,50-3150\ Hz}$ is the sound level difference calculated on the basis of the actual traffic noise spectrum in the particular place and the measured sound insulation in the frequency ranges 100-3150 Hz and 50-3150 Hz. The values have been converted to a reference situation where the window area = 2 m^2, the volume of the receiving room = 32 m^3 and the reverberation time in the receiving room = 0.5 s.

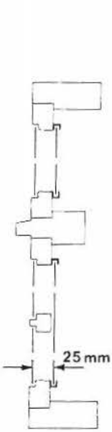
From this it appears that by the construction e (double construction with a glass insulating double unit mounted 13 cm from the original construction) there is a 5 dB difference between the sound level differences determined in the two frequency ranges. Several of the other constructions show the same tendency.

This is due to the fact that because of the resonance conditions these constructions have a low insulation in the frequency range 50-100 Hz at the same time as the traffic noise in heavy city traffic has a high energy content in the same



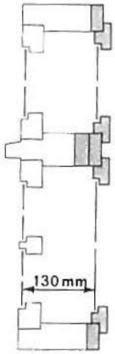
a. Original window

I_a = 25 dB
$\Delta L(A)_{eq}$:
100-3150 Hz = 30 dB
50-3150 Hz = 29 dB



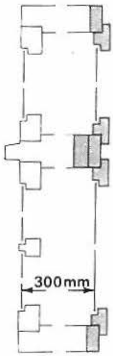
b. Single pane in plastic lists

I_a = 29 dB
$\Delta L(A)_{eq}$:
100-3150 Hz = 30 dB
50-3150 Hz = 30 dB



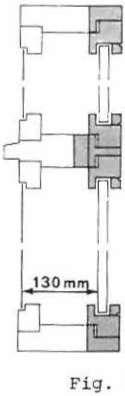
c. Single pane at a distance of 130 mm

I_a = 37 dB
$\Delta L(A)_{eq}$:
100-3150 Hz = 37 dB
50-3150 Hz = 34 dB



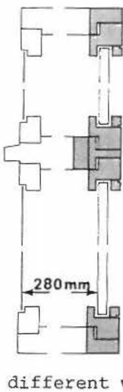
d. Single pane at a distance of 300 mm

I_a = 41 dB
$\Delta L(A)_{eq}$:
100-3150 Hz = 43 dB
50-3150 Hz = 41 dB



e. Glass insulation double unit at a distance of 130 mm

I_a = 42 dB
$\Delta L(A)_{eq}$:
100-3150 Hz = 45 dB
50-3150 Hz = 40 dB



f. Glass insulation double unit at a distance of 280 mm

I_a = 43 dB
$\Delta L(A)_{eq}$:
100-3150 Hz = 47 dB
50-3150 Hz = 47 dB

Fig. 4, measuring results for different window constructions frequency range. However, the frequency spectrum in the measuring place does not differ from frequency spectra registered by other investigations.

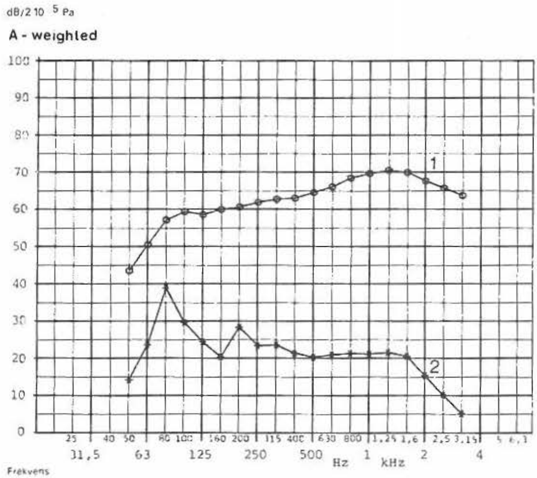


Fig. 5 - measuring result for object e, curve 1: sound pressure level 2 m in front of the façade. Curve 2: sound pressure level in measuring room, (both curves are A-weighted)

Fig. 5 shows a frequency analysis of the noise level outdoors and indoors for the measurement carried out in connection with construction e. The indicated levels have been adjusted within each 1/3 octave band in accordance with the A-weighinç so that it clearly appears which frequency bands are decisive for determining the dB(A)-level.

In the light of this, it must be concluded that measurings according to ISO 140 (in the frequency range 100-3150 Hz) are insufficient to obtain information about the sound insulation against traffic noise of some of these façade constructions.

Airborne sound insulation in buildings

In connection with several of the ordinary sources of noise occurring in buildings it has likewise turned out that the dominant sound transmission often takes place in the frequency range below 100 Hz. Thus, Leif Cederfelt (1) has shown that by using light, separating constructions as for instance plasterboard walls the sound level in the receiving room will be 7 dB(A) higher than is the case for a concrete wall with approx. the same I_a-value, (fig. 6).

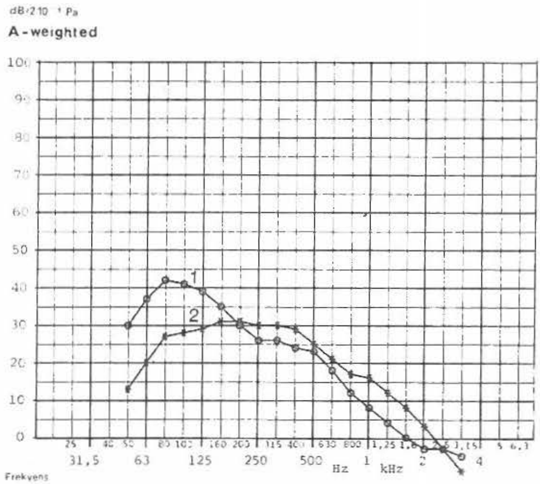


Fig. 6, according to Leif Cederfelt (1). Curve 1: calculated sound pressure level in the receiving room with a double plasterboard wall with I_a = 55 dB as partition. Curve 2: calculated sound pressure level in the receiving room with a concrete wall with I_a = 56 dB as partition. Both curves are A-weighted. As basis is chosen a "music-spectrum" in the source room according to DIN 45573

These problems are made topical through increased spreading of powerful HI-FI equipment with a good bass reproduction down to 20-30 Hz.

The Institute particularly faces the problem in connection with the establishment of discoteques, etc. in existing buildings. The Danish Building Regulations require an airborne sound insulation of min. I_a = 60 dB. Despite the fact that the stated requirements are fulfilled, complaints are often made because the sound transmission takes place in the frequency range below 100 Hz.

Impact sound insulation in buildings

When measuring the impact sound insulation in buildings, a standardized tapping machine is used in accordance with ISO 140, and the noise level from this machine is measured in the frequency range 100-3150 Hz. By light storey partitions the generated spectrum is quite different from the noise from footsteps, which is also the reason why this measuring method is not used in some countries. As, moreover, the recommended frequency range is probably quite insufficient in

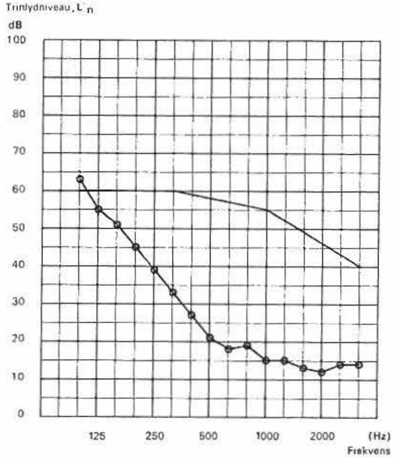


Fig. 7, impact sound level from a light storey partition with carpets.

relation to the practical conditions, it is obvious that disagreements between objective measurings and the users' perception of the sound conditions will be experienced.

It has not been possible to make a complete investigation of these conditions, and therefore we shall only refer to fig. 7, showing the measuring results from a storey building where repeated complaints have been made by the inmates because of impact noise from the neighbours. The I_i-values are 4-12 dB better than is required according to Danish legislation. By the investigations we noted considerable nuisance caused by impact noise from flats situated over the measuring room, and the curve measured in accordance with ISO 140 actually indicates a considerable increase in the level at low frequencies.

Discussion

In the light of this, it seems disadvantageous that ISO 140 and ISO R 717 do not deal with the frequency range below 100 Hz. In examples of the test procedure ISO 140 recommends - by measurings in buildings - a minimum volume of the measuring rooms of 25 m^3, corresponding to a lower limit of 100 Hz. The reason for this is that the inaccuracy of measurings is considerably increased - among other things because of fewer eigenmodes in the rooms. It should, however, be mentioned that ISO 140 states that measurings should be carried out <u>at least</u> in the range 100-3150 Hz. Therefore, measurings <u>can</u>, according to this standard, be carried out within a broader frequency range if only the inaccuracy of measuring can be stated.

ISO R 717, which is being revised at present, is more problematic. In this standard only evaluating curves for the determination of I_a (R'_w) and I_i (L'_w) in the frequency range 100-3150 Hz are indicated. Moreover, it seems as if the "8 dB-rule" will be removed. ("8 dB-rule" means that no single deviation from the evaluating curve must exceed 8 dB). This rule contributed to ensuring that by light constructions such as plasterboard walls and wooden storey partitions very low values of the insulation at for instance 100 Hz could not be accepted.

The "8 dB-rule" will - among other things - be removed because it increases the inaccuracy by the determination of I_a (R'_w) and I_i (L'_w) as these values in some cases will be determined by the sound reduction index, R', and the impact sound pressure level, L'_n, at for instance 100 Hz where the measuring inaccuracy is greater than is the case at higher frequencies.

It is extremely regrettable that the importance of the low-frequency range is put in a lower class to increase the reproducibility of the determination of these important figures. The result of this can only be an even greater difference between the objective criteria and the users' perception of the sound conditions.

Bibliography

1. Leif Cederfelt: I_a-værdien - en beskrivelse af lyd-isolation. Proceedings, NAS 1978.
2. Michael Lemke: Das Leerlaufproblem. Kampf dem Lärm 26, 1979.
3. L. Cremer: Die wissenschaftlichen Grundlagen der Raumakustik. Stuttgart: S. Hirzel, 1976.
4. ISO 140, Parts I-VIII: Measurement of Sound Insulation in Buildings and of Building Elements.
5. ISO R 717: Rating of Sound Insulation for Dwellings.

Conference on
Low Frequency Noise and Hearing

7–9 May 1980
at Aalborg University Centre
Aalborg, Denmark
Proceedings edited by
Henrik Møller and Per Rubak

ELIMINATION OF INFRASOUND GENERATED IN WATER POWER STATIONS

Ludwik Liszka
NATIONAL BOARD OF OCCUPATIONAL SAFETY AND HEALTH
Department of Occupational Health
Technical Unit
Box 6104
S-900 06 UMEÅ
SWEDEN

Bo Lundkvist
Kiruna Geophysical Institute
Box 704
S-981 27 KIRUNA
SWEDEN

In hydroelectric power stations infrasound is produced through a coupling of oscillations in the water flow in tubes and channels into the atmosphere. During certain operation conditions a considerable amount of energy, up to several MW of acoustic power, is radiated into the atmosphere.

The phenomenon is of considerable interest in the energy production; oscillations of water masses, in addition to energy losses (radiation of low frequency waves), seriously influence turbines, buildnings and other parts of hydroelectric stations. This is because oscillations add to a static load on different parts of the plant a dynamic component which accelerates ageing of the material.

In Sweden, a research programme dealing with low frequency mechanical oscillation in hydroelectric power stations has been carried on since 1974. In particular, mechanisms for generation of infrasound were studied. Recording of the infrasound in a station has an important practical application: it may be used as an early warning for a growing oscillation in the water flow. Especially in unmanned power stations a recording of the infrasound level gives an efficient method of detection of certain disturbances. An infrasound detector developed for this purpose is already in regular operation in a few hydroelectric power stations belonging to the Swedish State Power Board.

In addition to the methods of detection new methods for damping of low frequency oscillations in hydroelectric power stations have been developed. The oscillations have hitherto been considered as impossible to control.

As a hydroelectric power station has to be considered not only as a hydraulic but also as an acoustic system any changes of the coupling between its different parts will change the resonant properties of the system. One possibility in underground stations is to close drafttube shafts with air-tight covers. This method has been successfully used in the underground power station Sällsjö belonging to the power company Norrlandskraft AB. An average damping of about 20 dB within the whole frequency range of infrasonic oscillations has been obtained. At certain frequencies a damping up to 40 dB has been obtained. As an example the result of closing of the drafttube shafts at maximum power output (84 MW) from one of two generators (the second generator was in the shown example not in operation) on the frequency spectrum of oscillations is shown in Fig 1 (thick line). Also the frequency spectrum of oscillations with open drafttube shafts is shown in Fig 1 (thin line).

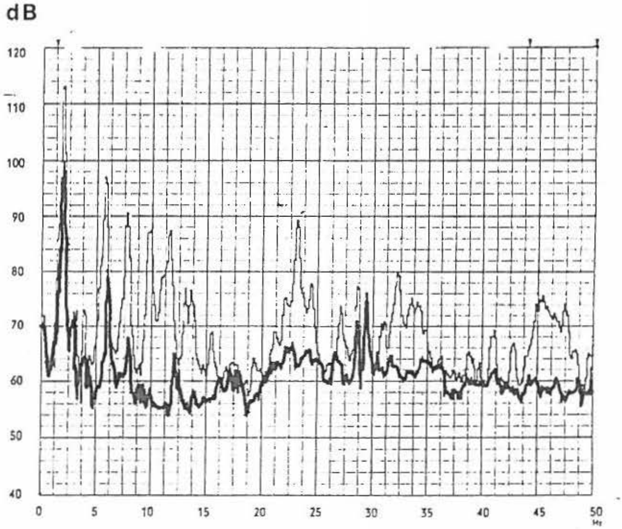


Fig 1. The frequency spectrum of low frequency oscillations (0-50 Hz) in Sällsjö hydroelectric power station at maximum power output from one generator. Upper curve (thin line): open drafttube shafts; lower curve (thick line): closed drafttube shafts.

The frequency spectra have been made using a 400-channel FFT analyzer (B&K). The measuring microphone (a modified B&K 4117 microphone) has been placed in the shaft below the cover.
Another method for damping of infrasonic oscillations is based on the fact that the sound velocity in water-filled tubes may be decreased from nominal 1497 m/sec down to as low as 290 m/sec by adding to the water a small amount of air bubbles (Pearsall, 1966). It has been proposed by Liszka and Lundkvist (197?) that the phenomenon may be used for elimination of low frequency oscillations in hydroelectric power stations. The method has been tested in

the underground power station Harrsele (3 generators 65 MW each) belonging to the power company Norrlandskraft AB. It has been found that the method decreases the oscillation amplitude within a wide range of frequencies. The positive effects are most pronounced on the turbine spiral. The vibration acceleration was found to decrease there in total to 1/3 of its normal value. At the lowest frequencies (<20 Hz) the difference is as large as 20 dB (see Fig 2). The result is of a considerable significance for decreasing of the ageing of material in the turbine. As turbine spirals are in large extent responsible for generation of low frequency audible noise in hydroelectric stations the method gives a considerable reduction of audible noise. The mentioned power station is now being equipped with permanently operating air compressors.

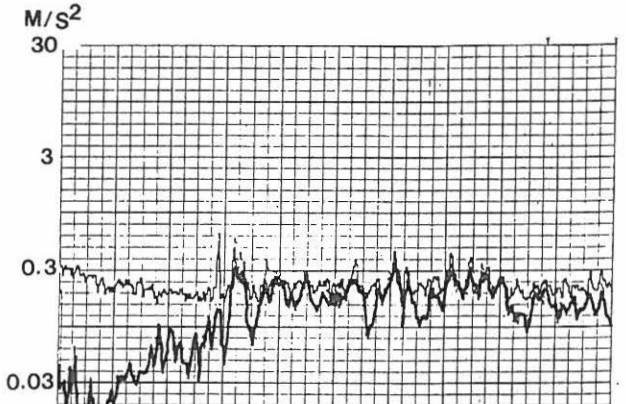


Fig 2. The vibrations spectrum in the turbine spiral (G3) of Harrsele hydroelectric station in normal operation (upper curve) and after introducing 3 m^3/min of air bubbles to the intake tube.

The added amount of air corresponds to less than 1 $^{o}/_{oo}$ of the water volume. The method is especially useful in power stations with dominating oscillations on the intake side of the turbine. The above methods are already in regular operation and may be used as an example of an unconventional elimination of infrasonic oscillations.

The present research was supported by the Board for Energy Source Development, Stockholm.

References

Liszka, L. and Lundkvist, B.: Low frequency oscillations in water tubes at Tuggen power station (in Swedish) KGI Technical Report 78:101. Februari 1978.

Pearsall, I.S.: The Velocity of Water Hammer Waves. Symp. Surges Pipelines, Proc. Inst. Mech. England Vol. 180, part 3 E, 1965-66.

Conference on
Low Frequency Noise and Hearing

7–9 May 1980
at Aalborg University Centre
Aalborg, Denmark
Proceedings edited by
Henrik Møller and Per Rubak

The influence of some elastomers on radiation and reduction of structure-borne low frequency noise.

Andrzej Rózycki,
"TECHPAN" Experimental Establishment,
Swietokrzyska 21,
00-049 Warszawa,
Poland.

Jacek Smurzyński,
Academy of Music,
Warszawa,
Poland.

Not available at the time of printing.

Conference on
Low Frequency Noise and Hearing

7–9 May 1980
at Aalborg University Centre
Aalborg, Denmark
Proceedings edited by
Henrik Møller and Per Rubak

Suppression of low-frequency noise of about 20 to 25 Hz in large compressors

Dr.-Ing. Juval Mantel
Dr. Mantel & Partners GmbH, Ingenieurbüro für Akustik
Simeonistr. 11, 8000 München 19

A c o u s t i c a Ltd.
Consultants for Acoustics,Control of Noise and Vibration
12 Geula Str., POB 5271, 31000 Haifa/Israel

Several large compressors and turbines used for compressing air in a sewage plant in Munich were generating air pressure waves in the frequency range 20 to 25 Hz and also beats. As a result of secondary effects these air pressure pulses were causing a nuisance in the neighbourhood, for several hundred metres across a busy main road. The low-frequency noise in conjunction with the high-frequency spectrum of the machines was not unduly loud owing to the noise of traffic. In the neighbouring houses, however, the noise had a pronounced effect owing to the window vibration. The rattling panes amplified the primary sound by up to 30 dB. To suppress the noise, a silencer with a sound absorption factor of 30 dB/20 Hz had to be designed and built. This was accomplished by combining a few physical effects such as diffraction, chamber silencing and absorption silencing. The values calculated and measured for the silencer components differed by 1 to 2 dB.

1. Problem

The settling basins at Grosslappen sewage plant in Munich are supplied with compressed air (0,4 bar) to accelerate the purification process. The following compressors and other equipment are accomodated in a machine room:

Table 1

No.	Equipment	Power (kW)	Air volume (m^3/h)	Pressure (bar)	RPM
1.	Diesel/ Gas motor (power source for compressors)	760	–	–	300-428
2.	Gas motor	760	–	–	300-428
3.	Gas motor	1045	–	–	300-428
4.	Piston Compressor	1900	39000	0,45	300-428
5.	"	1900	39000	0,45	300-428
6.	"	1900	39000	0.45	300-428
7.	"	1900	39000	0,45	300-428
8.	"	1900	39000	0,45	300-428
9.	Compressor turbine	2100	90000	0,45	1488,4350

The above equipment generates low-frequency noise both in the machine room and on the roof at the exhaust outlet and particularly at the intake port.

Spectral investigations in the immediate vicinity of the intake port, in the machine room, on the roof and at various distances in the vicinity affected yielded spectra with a maximum spectral component in the region of 20 to 30 Hz, depending on the operating speed of the machine.

Since the neighbours have no visual contact with the sewage plant for a few hundred metres (appropriate walls) and there is a busy main road intervening, it is only the extremely low frequencies of the compressors that affect neighbouring residents.

The (A)-weighted noise level is not so much due to the industrial noise described but rather to the noise of traffic. At traffic noise levels of 50 to 60 dB (A) and extremely fast decrease of the level to below 40 dB (A) the low-frequency spectrum components attain a value of 60 to 70 dB.

Since the window-panes of the neighbouring houses are large, the windows in almost every house were observed to resonate, thus reverberating and, in some cases, causing amplification and frequency displacement of the noise. This gave rise in certain parts of living-rooms to noise levels of up to 96 dB/31 Hz although the noise outside the house was below 70 dB.

As the noise source and the sound transmission paths /1/ were known, an economic concept was devised /2/ to minimize the machine room noise in the neighbourhood. The planning work /3 and 4/ culminated in an underground bunker (made possible by having roofs supporting a high weight per unit area) affording sound transmission loss and absorption. This bunker comprised a combination of three different sound level reducing facilities:

a. The intake air had to be diffracted by a barrier (see Figs. 2 and 3), thus causing a reduction of the sound level, particularly at high frequencies.

b. A chamber silencer with sound-absorbing walls and roof should afford additional sound level reduction in the narrow frequency range.

c. An absorption silencer as relaxation silencer was designed for the low frequencies, the length available being 15 m and the cross-section 30m^2 (for an air volume of 250,000 m^3/h) /5-6/.

This combination of the three physically different effects should provide the sum of the individual noise level reductions (with several similar processes the reduction effects may cancel each other) /9/. The individual facilities are as follows:

2. Barrier

Located at a distance of 200 m, i. e. half way between the machine room and the neighbouring residents, the wall gave very little sound diffraction, thus affording no appreciable reduction of the sound level. This barrier was particularly ineffective at low frequencies.

By incorporating a barrier in the form of a unnel which was directed 180° away from the neighbours involved, and which was also additionally provided with sound-absorbing lining (7,5 cm light wood fibre sheeting supplied by Heraklith) it was possible to detour the sound path several metres. At a wavelength of 17 m, which occurs at a low frequency of 20 Hz and zero temperature, an appreciable sound level reduction of approx. 9 dB/20 Hz can also be expected. To avoid sound reflection from the machine room (towards which the sound funnel was directed), a distance of over 40 m, i.e. more than two wavelengths and a few rows of trees were provided, the latter causing additional scattering of the sound. Such scattering is only possible with appropriate dimensions of the trees and distances between the rows.

3. Chamber silencer

With chamber silencers the noise level reduction above the natural frequency is expected to be entranced by 40 dB per decade. In practice, it is known that it is only possible to achieve noise level reduction of 30 to 40 dB at best, being mainly frequencies just above the natural frequency that are of interest. Although the natural frequency of the chamber silencer was relatively low, the reduction in the noise level achieved with the chamber silencer was not expected to exceed 30 dB. It was even assumed that only 12 dB/20 Hz would be reached.

Since exact calculation of chamber silencers is extremly difficult, it was decided to dimension the absorption silencer at a later time, once the chamber silencer and barrier have been installed. It was found that the two foregoing facilities (barrier and chamber silencer) together afford a reduction in the sound level of 18 dB/20 Hz, a further reduction of 12 dB/20 Hz thus still being necessary to reach the total target of 30 dB/20 Hz.

4. Absorption silencer

The absorption silencer should afford a 12 dB/20 Hz reduction in the noise level. Older /7/ and more recent /8/ calculation methods allow the noise level reduction (sound absorption) in relaxation silencers to be determined, provided that the exact technical data of the materials are known. In practice, it is found that exact characteristic data are not available. Errors of - 50 % to + 100 % are quite possible. It was therefore suggested that the absorption silencer be assembled from a few successively connected units so that cross-sectional discontinuities in the absorption silencer can provide additional absorption.

5. Final remarks

Compressor noise which was generating levels of 60 to 70 dB /20 Hz at a distance of several hundred metres, but which was producing up to 96 dB/31 Hz in closed houses made it necessary to reduce the noise level. One of the biggest silencers in the world was planned and manufactured in the form of a subterranean bunker ensuring sound transmission loss. At the time of going to press the absorption silencer had not yet been installed, and so no data on this part of the project are available at present.

6. Literature

/1/ Report No. 7478, dated July 21, 1974, Dr. Mantel & Partners GmbH München, Ingenieurbüro für Akustik

/2/ Report No. 7478/I, dated September 16, 1974, Dr. Mantel & Partners GmbH München, Ingenieurbüro für Akustik

/3/ Report No. 76105/I, dated October 1, 1976, Dr. Mantel & Partners GmbH München, Ingenieurbüro für Akustik

/4/ Report No. 76105/II, dated October 22, 1976, Dr. Mantel & Partners GmbH München, Ingenieurbüro für Akustik

/5/ Report No. 76105/III, dated September 24, 1977, Dr. Mantel & Partners GmbH München, Ingenieurbüro für Akustik

/6/ Report No. 76106/IV, dated October 10, 1978, Dr. Mantel & Partners GmbH München, Ingenieurbüro für Akustik

/7/ Beranek "Noise Reduction", Mc Graw-Hill, 1960, New York

/8/ Mechel, in Heckl, Müller "Taschenbuch der technischen Akustik", Springer Verlag, Berlin 1975

/9/ Mantel "Noise Control at Audible Sound and Infrasound Frequencies", First Haifa International Symposium on Industrial and Applied Acoustics, April 9, 1980

LUFTSCHALLPEGEL (MASCHINENPAAR)

MESSPUNKTE : ANSAUGSCHACHT

AGGREGAT : 5 6 7 8 (9)

DREHZAHL : 400 UPM

DATUM : 74 - 6 - 25

TRÄGHEIT : SLOW

Fig. 1

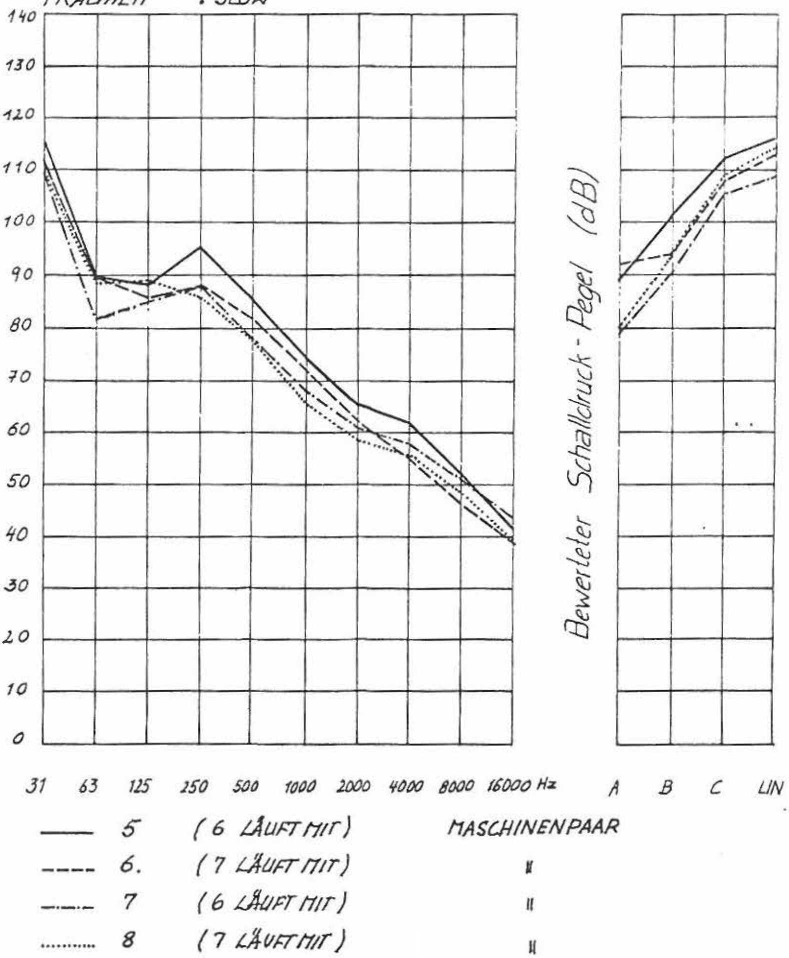


Fig. 2

Points of Measurements (1978)

m = 1 : 1000

I - II on surface

IV - VI in subterranean silencer

A = Air Intake

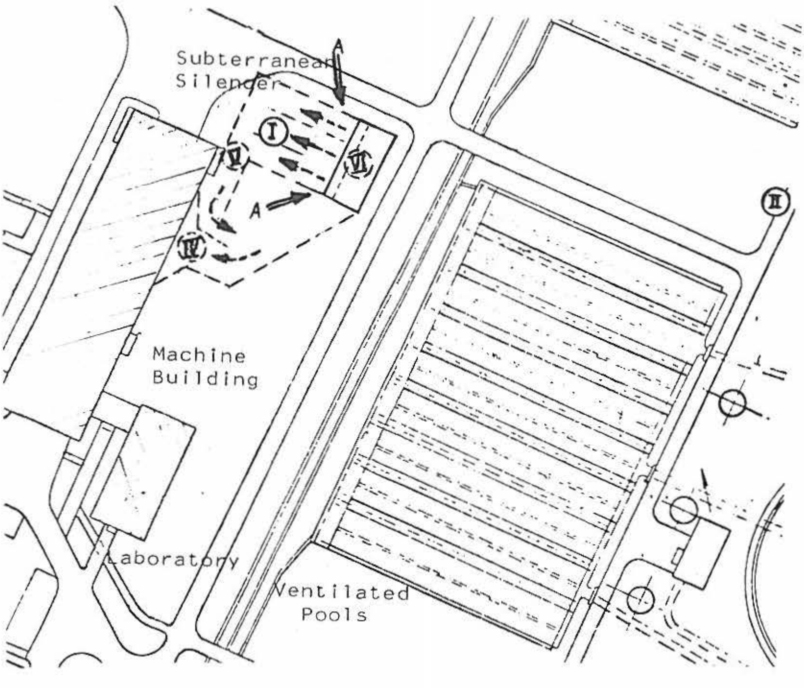


Fig. 3

A = Air Intake

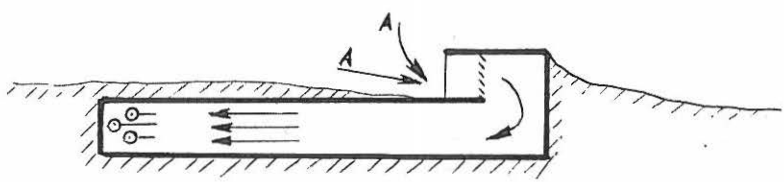
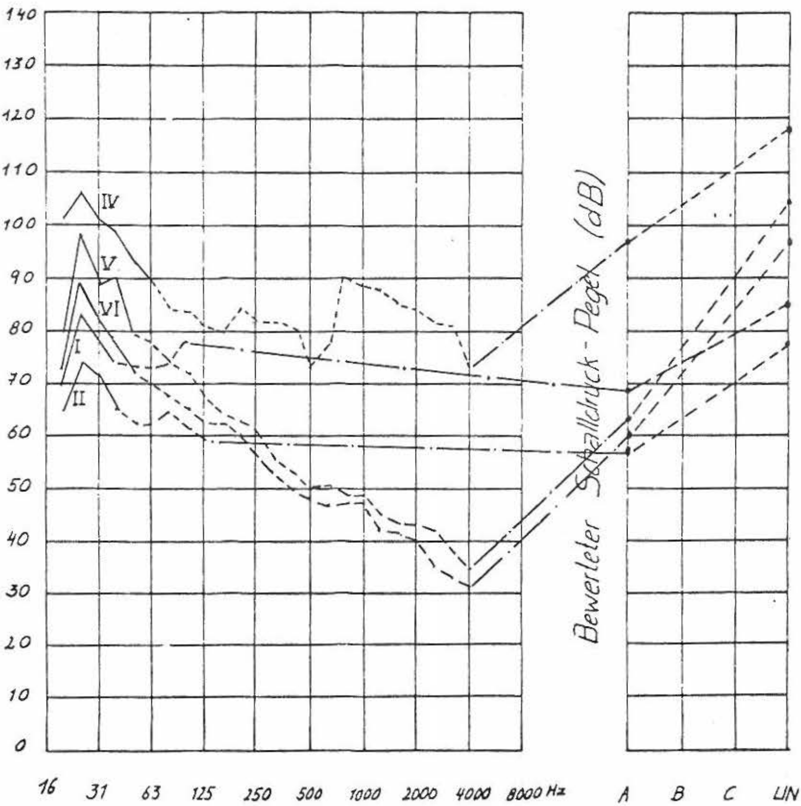


Fig. 4

1/3 Octave Noise Spectra (1978)

dB Overloading ------



INDEX OF AUTHORS:

Notes.

Notes.

Notes.

Notes.

Notes.

Notes.

Notes.

ISBN 87-7307-061-0